March 1958

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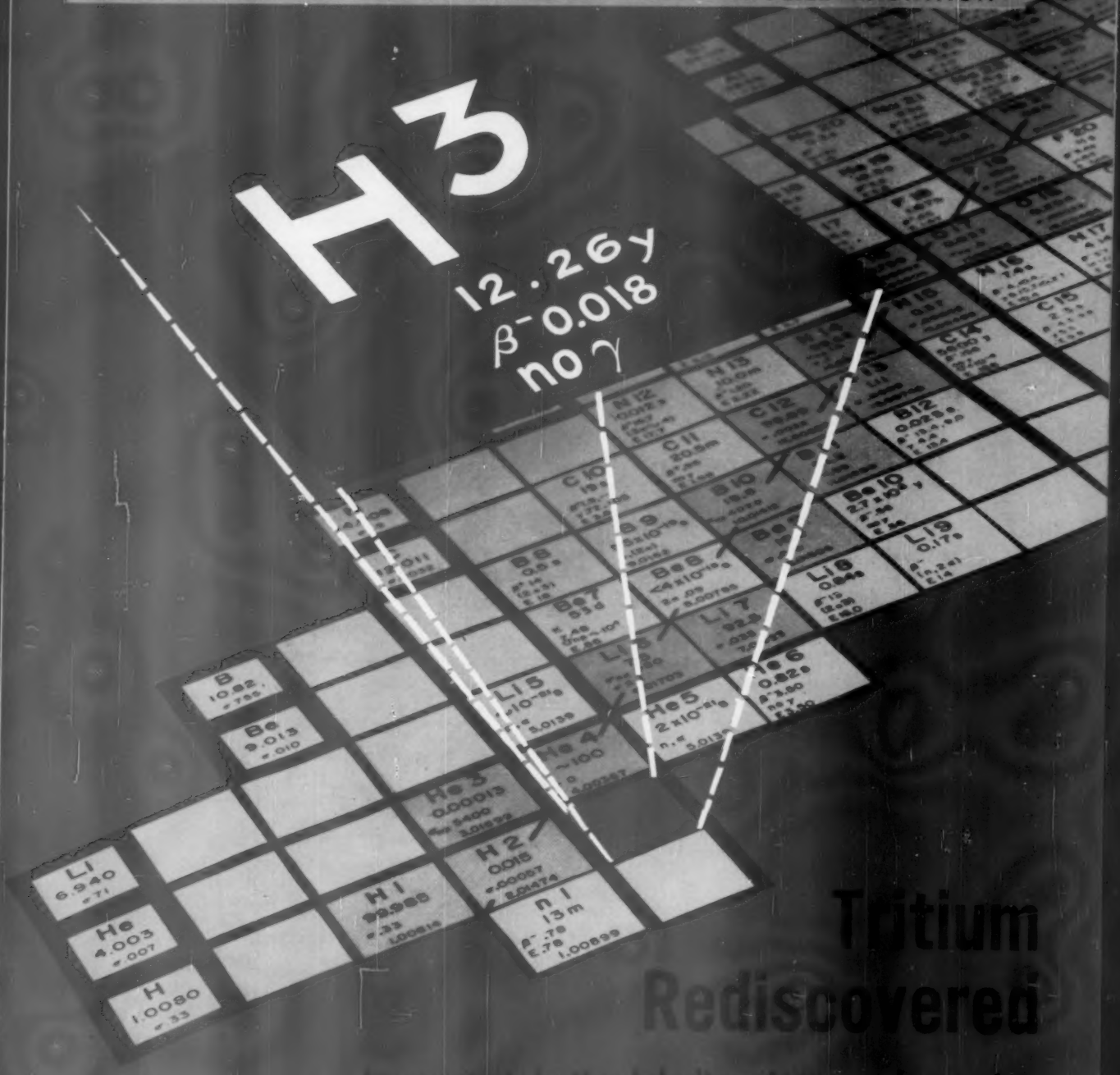
NUCLEONICS

ATOMIC POWER • NUCLEAR ENGINEERING • APPLIED RADIATION



Tritium Rediscovered

Lower cost, better labeling, improved counting lead to greater use . . . page 62

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N-220PT SCALER

The N-220 Series Decade Scalers are low-cost, fast, and versatile counting devices, employing three in-line decades and a four-digit electromechanical register.

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VOLUME 16 NUMBER 3

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About NUCLEONICS

We'd like you to meet

We'd like to introduce to you, all 20,000 of you, Assistant Editor Bob Adamson, the latest addition to our editorial staff. Bob will be working with John Kenton, our News Editor, in covering news developments in the nuclear field. With two news editors and six technical editors we'll be in a stronger position than ever to cover all facets of the nuclear field.

Now, the editorial staff of NUCLEONICS is too young for us to ask the editors to write their own obituaries but we did call on Bob to provide his own introduction; it follows as he wrote it:

BOB ADAMSON, newest member of the Nucleonics editorial staff, who joins our news department

"The newest member of our editorial staff is a replanted Yankee–replanted too late, he says, to affect seriously his ten years of exposure to the 'rural' life of Washington, D. C., and points south.

"Bob Adamson, assistant news editor to John E. Kenton, is a 30-year-old New Jerseyite who 'went south for an education' in 1948. A newspaperman with a three-year history in nucleonics, he entered the field six months after the 1954 atomic energy act gave rise to a private nuclear industry. He found an immediate excitement and attraction in the atom which inevitably led him to his new post, after covering atomic energy first for a weekly newsletter and then for a daily newspaper.

He has a typical newsman's education—heavy on journalism and social sciences—with the atypical extra of considerable time in television and radio writing. After two years at Rutgers (including an enjoyable but inglorious stint as captain of the jayvee football team), he completed his education at American University in the District of Columbia. His diploma, dated June 1950, carries the 'suspect' degree of bachelor of science (all social).

As a family man of just over a year with a "Texas redhead" and 4-month old daughter to match, he suspects he will have much to contribute to the school of large families—if he survives. His other interests are boating, the theater, a category termed 'Lincoln and literature' and most outdoor activities he has had time to try.

His philosophy in life was voiced by James Branch Cabell's hero in *Jurgen:* 'I'll taste any brew once.'"

Tritium Rediscovered

Associate Editor, Hoby Ellis (newly promoted along with John Kenton and Hal Davis, c.f. masthead) is the conveyor of the happy phrase "Tritium Rediscovered" that we use on the cover to proclaim our story on important new developments in the field of tritium labeling and counting (p. 62). Hoby developed that story by attending a symposium on the applications of tritium sponsored by New England Nuclear Co., Atomic Associates, and Packard Instrument Co.

We think this idea of private industry sponsoring nuclear meetings is a good one and are glad to note the current trend in this direction marked by such examples as Tracerlab's Houston meeting on tracer applications in oil industry and Columbia-National Corp.'s meeting on the economics of zirconium vs stainless steel (NU, Feb. '58, p. 24).

While we're extending credits we'd like to thank the General Electric Co. for permission to reproduce their well-known Chart of the Nuclides as part of our cover this month.

Where's PWR?

Those of you who read this page carefully note that the lower right-hand corner is given over to coming features. Last month we promised that *this* month we would have Reactor Foldout number 5 on the Shippingport PWR. It has turned out that we have been able to arrange for a cracker-jack full-scale report on PWR to be included in our April issue. Thus, we have held up on the foldout in order to give you the more complete story that is now available.

—*The Editors*

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Coming Features in NUCLEONICS

Next Month

A NUCLEONICS Report—Shippingport PWR

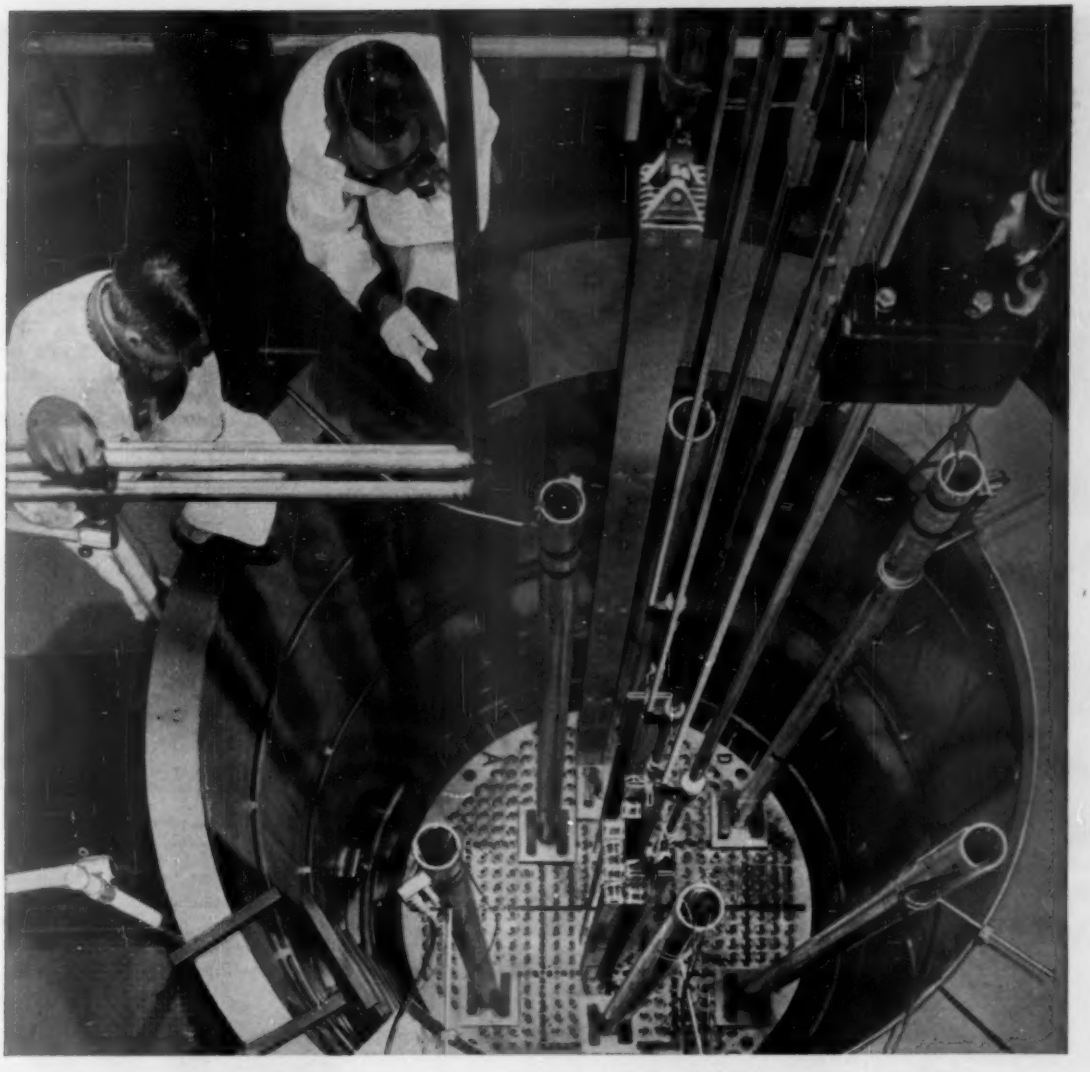
Data Sheet No. 23—Fission-Product Yields

Chemical Control of Reactors

Later Months

Scintillation Counter Symposium

Special Report on Reactor Control



FORECASTING CORE PERFORMANCE

A nuclear power plant requires exact knowledge and control of the quantity and arrangement of the nuclear fuel. To determine precisely the operating nuclear characteristics and performance of B&W's full scale reactor cores, the company maintains a critical experiment laboratory at its specialized nuclear research facilities in Lynchburg, Va.

Critical experiments are conducted at virtually zero power, permitting economical, safe analysis of the proposed fuel cores and the gathering of nuclear data for their final design. Flux distributions in the reactor core are measured with foils of different elements which become radioactive under neutron bombardment.

In this way, the calculations of physicists and engineers can be confirmed or modified; optimum quantity and arrangement of fuel elements and control rods can be determined; the core's ultimate power distribution, safety and stability can be established; and a more accurate forecast of the conversion ratio and reactivity lifetime of the core is made possible.

This privately-financed critical test laboratory is just one example of B&W's investment in facilities, engineering, and research to put nuclear energy to work constructively and economically. The Babcock & Wilcox Company, Atomic Energy Division, 161 East 42nd Street, New York 17, N. Y.

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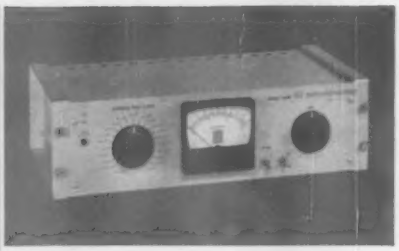
*** Model 420**

LOG N AND PERIOD AMPLIFIER

THE 420 is a dual monitor of power level and reactor period. It measures current from 10^{-13} to 10^{-6} ampere and positive or negative reactor period from 30 to three seconds. Zero drift is less than 0.05 decade in eight hours; response speed is adjustable over a wide range.

Other features include five-second recovery from overloads, self-calibration, and separate outputs from remote meters and recorders. (Contact-meter models also available.)

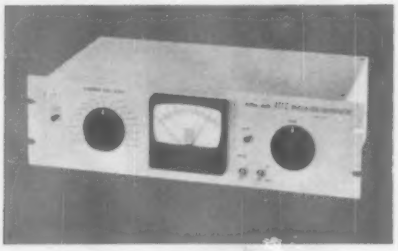
$950.00



linear micro-microammeters

Model 410 has 20 ranges from 10^{-13} to 10^{-3} ampere. Features include zero drift of less than 2% of full scale per 24 hours. Accuracy: 2% of full scale on 10^{-3} to 10^{-8} ranges, 4% on other ranges. Fast response; no switching transients. (Model 411 with fewer ranges and less drift also available.)

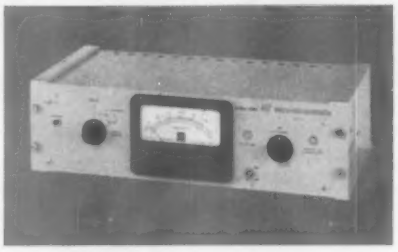
$490.00



contact-meter models

The 410-C furnishes economical control or alarm circuitry. A meter-relay with adjustable contact replaces the panel meter. 5-ampere contacts are brought out through an AN connector. (Model 411-C also available.)

$625.00



logarithmic models

The 412 Log n Amplifer has a large single scale, measuring 10^{-13} to 10^{-7} amp. with no range switching. Other features include zero drift within 0.05 decade in 24 hours, fast response and low output noise. (Model 413 with 10^{-11} to 10^{-5} ampere range also available.)

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Phosphoric Acid	excellent to fair below 85%	poor
Chromic Acid	excellent	excellent to good
Aqua Regia	poor	excellent
Wet Chlorine Gas	poor	excellent
Chlorine Water	excellent	excellent
Sodium Hydroxide	good below 90%	good below 50%
Ferric Chloride	poor	excellent
Calcium Chloride	excellent	excellent
Cupric Chloride	poor	excellent
Sodium Chloride	excellent	excellent
Ammonium Chloride	excellent	excellent
Aluminum Chloride	excellent	excellent to fair

Chart shows corrosion resistances of zirconium and titanium to typical chemicals.

Steam jet made of zirconium, which has given trouble-free performance after a year in hydrochloric acid service. For comparison, a throat piece from a steam jet (below) is shown after only a week of similar service.

By specifying titanium or zirconium for processing equipment, you can now overcome most of the corrosive media which attack other metals.

Even with such hard-to-handle chemicals as chlorides and oxidizing acids, equipment can have extremely long service life when made from these corrosion-resistant materials. Problems of product contamination in chemical and food processing can also be virtually eliminated.

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Titanium is now available from stock in a complete range of mill products, may be readily fabricated, and more than pays its extra cost where ordinary metals fail. Zirconium facilities are being rapidly increased, and mill shapes are now in production.

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COLLEGES AND UNIVERSITIES COMPLETE NUCLEAR

A typical student nuclear engineering laboratory. At the left background is a well scintillation counter, scaler, and timer. On the same bench at the right is an automatic strip foil analyzer. An alpha survey meter and beta-gamma survey meter rest on top of the bench.

To the right, in front of an automatic gamma-ray recording spectrometer, a student surveys the area with a portable slow/fast neutron monitor. At the reactor, students make measurements within the uranium lattice with BF_3 counters.

At the right a student uses a scintillation detector in a manual sample changer. Beside him are two student counting systems. On the table in the foreground is an ion chamber type survey meter. These instruments, manufactured by Nuclear-Chicago, are all typical nuclear training tools which will contribute importantly to any nuclear engineering curriculum.

Instructor demonstrating insertion of aluminum tube into grid assembly in the Model 9000 Student Subcritical Reactor. 275 of these tubes, containing uranium fuel in the form of 1″ x 8″ slugs, are arranged in a hexagonal pattern in the reactor. Since the moderator is water, students actually can see the exact position of a detector or foil placed at any point within the uranium lattice.

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Complementing the Student Reactor is a carefully selected, integrated group of radiation detection and recording instruments. Designed for both group and individual experiments, the instrumentation includes gamma-ray scintillation spectrometer assemblies, fast and slow neutron counting systems, foil counters and analyzers, student alpha, beta, gamma counting systems, and portable monitoring instruments.

Nuclear-Chicago supplies a manual providing detailed instructions on more than 30 nuclear experiments directly related to the Student Reactor and associated nuclear instrumentation. Experiments are designed to familiarize students with basic nuclear detecting and measuring devices and analytical methods, and to provide actual reactor work in determination of neutron flux, neutron activation, and other reactor properties. A typical course outline will be supplied by Nuclear-Chicago and special programs can be prepared to meet the particular needs of any educational institution.

Nuclear-Chicago is the only manufacturer able to provide a Student Reactor, complete instrumentation, and the nuclear course curriculum. For full information, write Nuclear-Chicago today expressing your interest in this vital addition to your training and teaching facilities. A representative will call on you, explain complete details of the AEC assistance program, and give help on making requests for funds and fissionable materials from the Atomic Energy Commission.

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Instructor loads reactor with neutron source which is generally placed in the center of the uranium lattice. Calibrated mechanism supplied with the reactor may be used to position source anywhere within the structure for experimental purposes.

Strip Foil Analyzer is one of several systems for group experiments. Strip foil activated in reactor is drawn automatically past Geiger tube in analyzer. Recording shows exponential decrease in activity along radius of uranium lattice.

Typical student counting system for individual experiments includes scaler, timer, manual sample changer with thin window Geiger tube, absorber set, alpha-beta-gamma source kit, and set of uranium, silver, gold, and indium foils.

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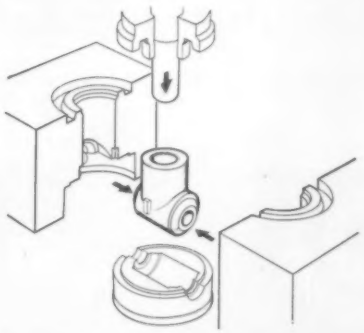

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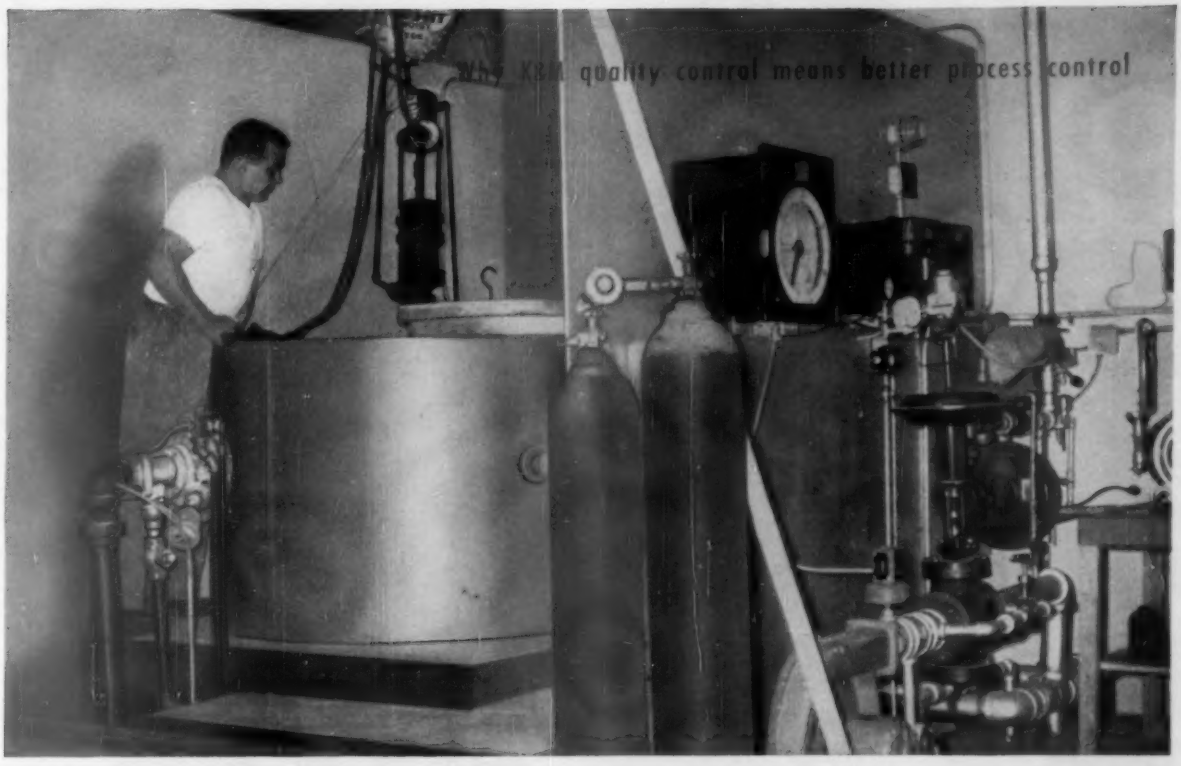

A BREATH OF HELIUM SNIFFS OUT HIDDEN VALVE FLAWS

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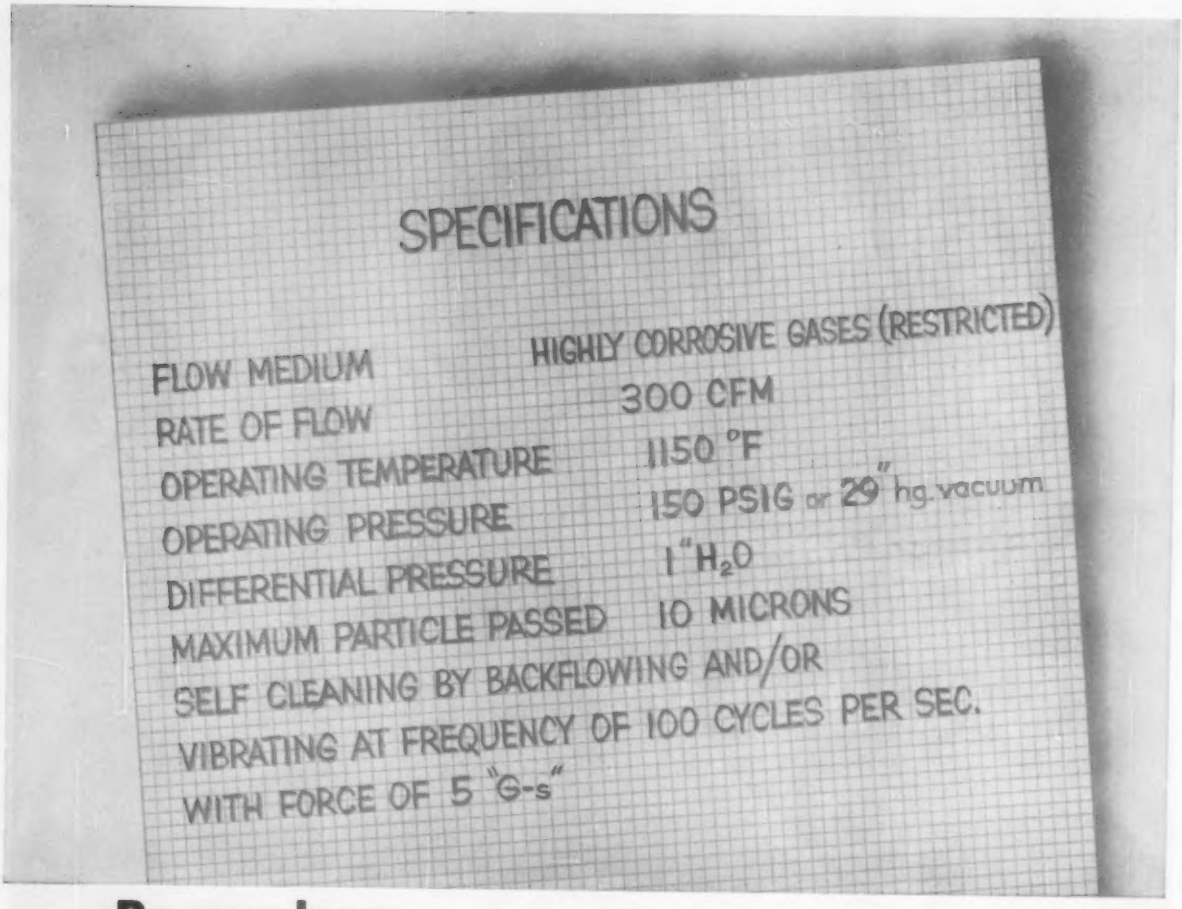

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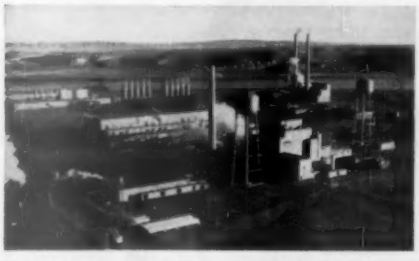

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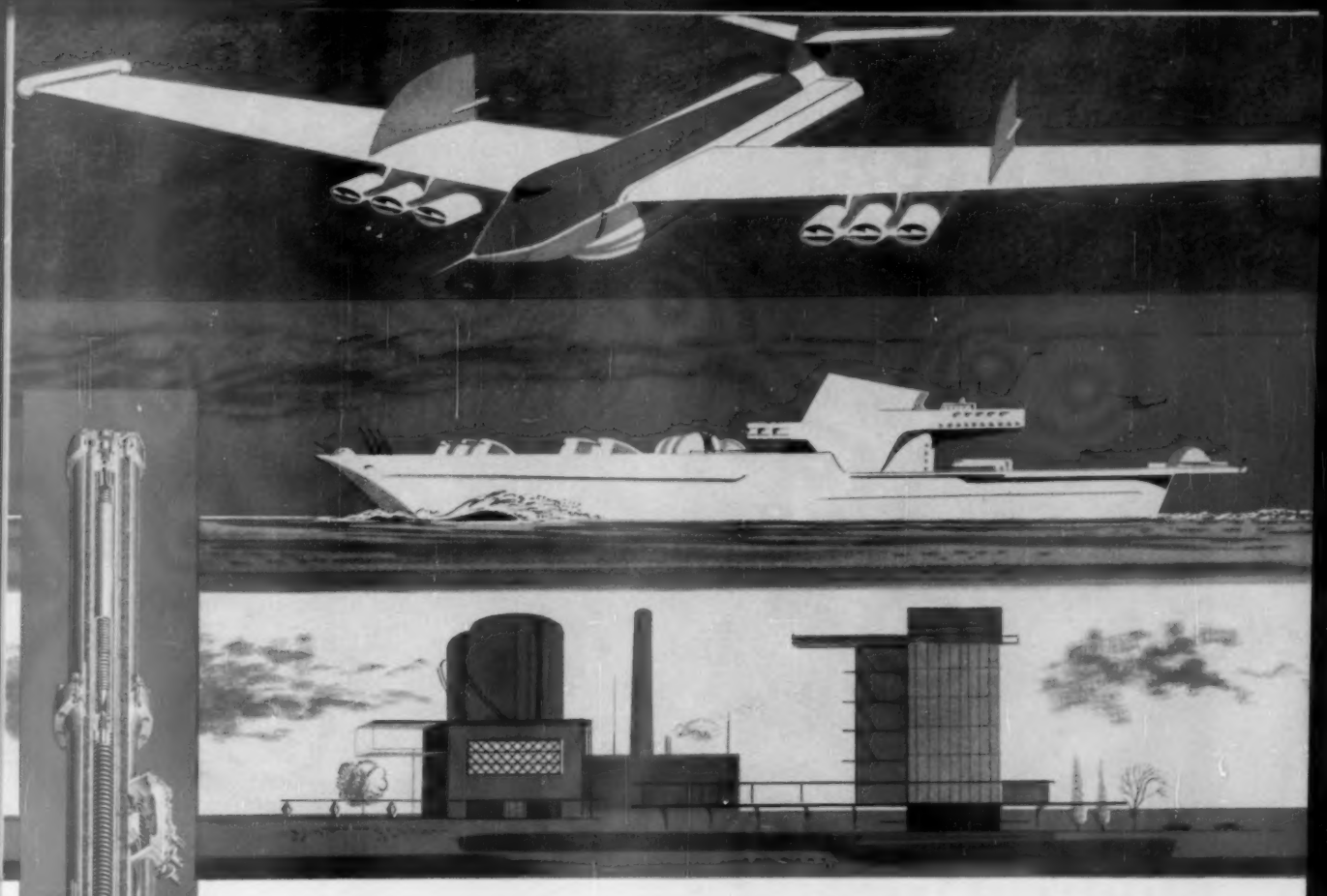

nuclear core control mechanisms

FOR ATOMIC REACTORS

Vard, with more than fifteen years experience in the design and manufacture of ballscrews and acme screw actuators for the aircraft and missile industry, is now engaged in the production of nuclear core control mechanisms for atomic reactors.

Vard facilities are equipped to manufacture all components; weld, plate, assemble and test complete mechanisms.

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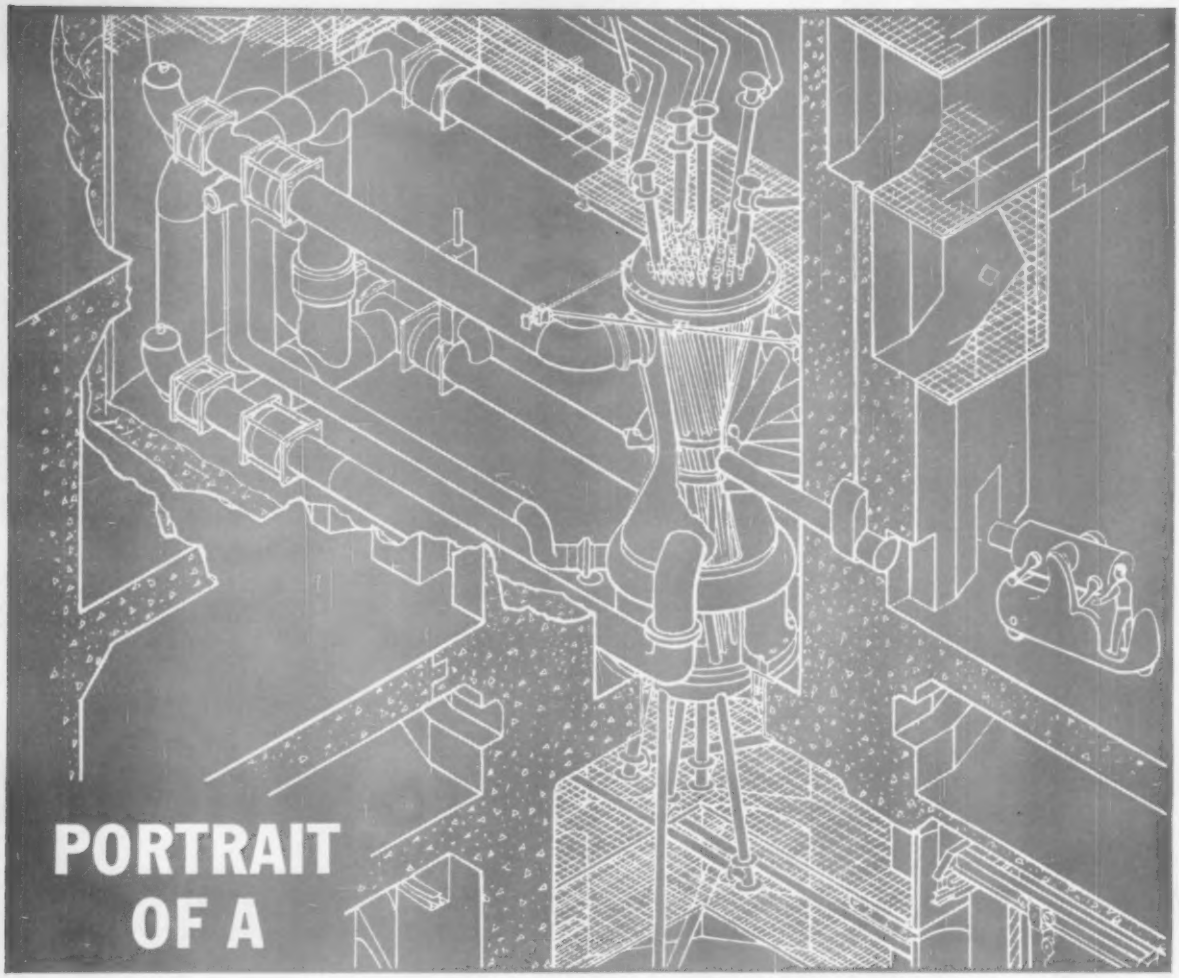

TEST REACTOR

Five nuclear reactors are in various stages of development at NDA. Each differs from the others, but all bear the stamp of true progress.

Progress in design is an NDA hallmark and accounts in part for its success in a demanding field. Equally important, however, is the ability of an organization to move from concept through engineering design, materials development, laboratory experimentation and critical testing. In these, too, NDA's reactors show invention and originality.

NDA's complete reactor capabilities are exemplified in METR (above), a 50-megawatt Materials and Engineering Test Reactor, the first of which is now under construction at Mol, Belgium. Beginning with the core itself, a unique design which combines extremely high neutron flux with simple, independent access to each fuel and experiment tube, METR I will be a vital part of one of the world's great nuclear centers. METR is typical of the family of reactors now under design or development at NDA for power, propulsion and research.

OPPORTUNITIES EXIST AT NDA FOR QUALIFIED SCIENTISTS AND ENGINEERS

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ROUNDUP of Key Developments in Atomic Energy

Foreign Demands Forcing Acceleration, Hearings Show

Promise of agreement between Congress and industry on goals of the U. S. atomic power program was held out at the fourth annual "202" hearings on the state of the atomic industry, which began Feb. 19 before the Joint Committee on Atomic Energy. Although there was no agreement on means of implementing such objectives, an enlivened interest on the part of both government and industry in the foreign reactor market as one route to our objectives was clearly manifested.

However, the success of protracted efforts to achieve harmony between JCAE and AEC in the drafting of a statement defining basic U. S. nuclear power objectives remained very much in doubt. An uneasy truce, postponing until the end of the hearing AEC's statement to JCAE of its current views on private industry's role in nuclear power development, left the situation up in the air as this issue went to press; however, NUCLEONICS learned that an area of agreement has been defined and awaits approval by the Budget Bureau for the White House.

The promise of agreement glimmered as industry put into the record of the Joint Committee these attitudes, jelling over the past year (and supporting the findings of NUCLEONICS' survey last month):

- that there should be some form of acceleration;
- that whatever its form, substantial federal money will be needed;
- that private industry should play a major role—and, according to industry, should be subsidized in that role;
- that a 10-year, $1–2-million acceleration program may be needed to meet foreign policy objectives;
- that our foreign policy requirements should be the dominant factor in determining the pattern of any program acceleration;
- that independent of acceleration, some administrative steps must be taken by AEC to improve industry's export position, chiefly reduction of the effective cost of nuclear fuel to foreign customers and long-term guarantee of supply.

Still far from solution are such major problems as:

- the roles of government and industry in building power reactors.
- whether foreign policy objectives would be better met by building reactors on U. S. soil, or in foreign territories, or both.

Feudin' an' Fightin'

The running feud between AEC chairman Strauss and JCAE Democrats erupted anew when Strauss was accused of breaking an agreement with the Committee to postpone discussion of the power program until the end of the hearings (tentatively set for mid-March). His reading of a telegram from Pacific Gas and Electric announcing its Humboldt Bay reactor project (*see story this page*) loosed a bitter attack by Sen. Clinton P. Anderson (D–N.M.) and other Democrats.

AEC had already prepared its power program testimony in writing (largely a report of progress to date) when postponement of the controversial issue was proposed by James Ramey, JCAE staff director. Ramey wanted time while he sought to complete negotiations with AEC general manager Kenneth E. Fields on a statement defining long-range U. S. reactor goals and to get the resulting policy paper approved by the Budget Bureau. Such a jointly-endorsed statement of government objectives was suggested in November by JCAE chairman Carl T. Durham; a tentative draft was discussed at high level in December, and Ramey has since been shuttling between the Capitol and AEC trying to obtain full agreement.

Within this patchwork of near-agreement and disagreement, AEC

Reactor project news from JCAE hearings

Pacific Gas & Electric announced—in a wire to Lewis Strauss read by the latter to the Joint Committee—that it is undertaking a 60-Mw(e), $20-million privately-financed boiling reactor, and is contracting with General Electric for the nuclear equipment and with Bechtel to be architect-engineer on a turn-key fixed-price basis. Site is PG&E's Humboldt Bay plant south of Eureka, Calif.; completion date is 1962–63. Fuel will be 2% enriched; single-cycle unit will be largest with natural circulation. PG&E claims second core will achieve competitive power at 8 mills/kwh.

Florida West Coast–East Central Nuclear groups have received a "letter of intent" from AEC for their 50-Mw(e), heavy-water-moderated gas-cooled project (NU, Jan. '58, 17) subject to Congress' approval. AEC has been asked to put up $5-million in initial research-development funds, $1-million in use of its facilities, $2.5-million in later development if progress warrants; matching amounts would be spent by sponsors. The research-development contract would provide: that AEC would decide feasibility of construction, and that the Florida utilities could withdraw if an improved concept came along, or if a panel of engineers named by both parties found prospective costs of nuclear heat to exceed 150% of conventional. The utilities are willing to carry an annual operating overburden of $1-million.

Atomic International's Chauncey Starr reported "very, very successful results" with the Organic Moderated Reactor Experiment AI built for AEC in Idaho. Starr said, "We have made a proposal to a European utility for a 100-Mw organic-moderated reactor, and to another one [the SENN group in Italy] for a 150-Mw."

and industry witnesses had a substantial number of suggestions on the need for and direction of reactor acceleration. These fell in the two areas of domestic and foreign activity, the latter getting more attention this year than in the past.

Limited on what it could say about the domestic program, AEC said it was considering a number of approaches designed to strengthen the competitive position of the U. S. reactor industry abroad and, simultaneously, advance the development of nuclear power in the U. S.

"We are sanguine that the programs finally adopted will meet these objectives," Commissioner Floberg declared. The programs are due for submission to JCAE this month or next for action this year.

The Starr Plan

Chauncey Starr, general manager of Atomics International, suggested a subsidy scheme to guarantee U. S.-sponsored reactors for foreign utility customers at little or no more cost than a fossil-fueled power station of the same size. Under the Starr plan, the U. S. would fund capital costs exceeding those for a conventional plant and sell the reactor heat at the price of fossil heat in the site country.

Lee L. Davenport, president of Sylvania-Corning Nuclear Corp., called for construction of 5–10 reactors in the U. S. within five years, programming them to generate 15-mill power at an installed plant cost up to $300/kw of capacity. He also called for U. S. subsidy of "up to 50%" of the cost of U. S. reactors built abroad.

W. D. Leggett, Jr., vice president of Alco Products, suggested a $50–100-million subsidy program for domestic acceleration; AEC would assume possibly half the excess of nuclear costs over conventional costs. He also urged steps to assure prospective foreign purchasers of reasonable fuel costs and life-of-reactor fuel supply.

Philip N. Powers, president of Internuclear Co., declared flatly that "the best way to give strength and direction to the [domestic program] is to focus its attention on, and orient it toward, meeting the immediate requirements for nuclear power development abroad." He offered the view that this tack might bypass "our difficult domestic problems" but permit acceleration of U. S. reactor development.

John C. Linsenmeyer, executive vice president of American Standard, recommended government construction of pilot-size plants for promising concepts, but said large-scale versions "should in the main be constructed abroad." He also demanded a bolder government policy on space and process heat reactors and clarification of the third-party liability problem abroad.

Willis Gale, chairman of Commonwealth Edison, urged direct subsidies to public and private utility firms, roughly in the ratio of existing generating capacity owned by each segment. The government should pay "a substantial part, but not all" of costs over those justified competitively, he said.

Kenneth A. Spencer, spokesman for the National Coal Assn., made a three-part recommendation: 1. encourage greater industry participation in AEC services; 2. limit large-scale reactor construction to technological needs; and 3. make it easier for U. S. equipment firms to compete in the foreign market.

Eyes on Foreign Market

This year's 202's have shown stronger interest from all sides—AEC, JCAE and industry—in the foreign market. AEC took a step in promoting U. S.-foreign reactor arrangements when it asked Congress in January to authorize long-term plutonium purchase contracts with foreign reactor owners (up to 15 years). Floberg testified that AEC has taken or is considering others steps: equal treatment with U. S. reactor owners on fuel reprocessing charges by AEC; the effect of lack of foreign indemnity on prospective U. S. sales; and, working with the State Dept., a solution to the third-party liability problem.

JCAE chairman Carl Durham (D.-N.C.) and Rep. Chet Holifield (D.-Cal.) gave a hearty reception to the Starr plan for U. S. subsidy of capital and fuel costs. A similar plan was offered previously in Congress by Reps. Sterling Cole and James Van Zandt. Durham told NUCLEONICS that he gave an acceleration program pegged to encouragement of U. S. competition in the foreign field a good chance of approval this year. He was not so optimistic about a domestic construction program.

Starr emphasized that he envisions a foreign reactor subsidy program as a part of U. S. technical development program. In short, he would insist on limiting subsidy to projects which would advance the art. Subsidizing the fuel costs of five 60 Mw(e) reactors and five 200 Mw(e) plants, Starr estimated, would cost the U. S. $30-million for the first ten years and something less than that thereafter as costs are trimmed through techological progress. He indicated this was based on 12–15 mill nuclear power.

To subsidize the difference between conventional and nuclear capital costs for the same reactors, he estimated, would cost something over $130 million. Total estimated U. S. cost to support his 10-reactor program—$160 million.

"Fortunately," he testified, "this international goal can be accomplished as an integral part of our national planning for the development of competitive atomic power."

Other 202 highlights:

- Commissioner Libby said AEC has asked Congress for $5 million to support increased exploitation of radioisotopes. The money request, covering the fiscal year beginning July 1, would fund: 1. a program to encourage AEC-industry cooperative efforts to find new and exploit known uses; 2. a program to accelerate economic application of high level radiation to industrial uses; 3. a program to train industrial personnel in the use of radioisotopes and nuclear radiation; and 4. a program to provide incentives for private production of radiation facilities and radioactive materials.
- Paul W. McDaniel, acting director of AEC's research division, disclosed that consideration is being given to expanding the controlled fusion program; specifically under review are two proposals to go to "larger instruments."
- Edward Diamond, under critical questioning by Committee Democrats, said the AEC has claimed no atomic energy patent for public use under special language in the 1954 Act making this possible.

AEC Loses Booth

Chairman Strauss told JCAE that a "conflict of interest situation" had recently prevented AEC from recruiting "a very competent man." He was Eugene Booth, who took a 2-year leave of absence as head of the Physics Dept., Columbia Univ., last November to become director of AEC's research division. However, a pending patent claim against the government forced cancellation of the plan to hire him. Paul W. McDaniel has been acting research director since the post was vacated Sept. 30 by Thomas H. Johnson, now research chief at Raytheon.

Japan Asks British Bids On First Power Plant

Three British engineering groups have been invited to bid by July 31 on construction of an atomic power station in Japan. The reactor will be a natural uranium, graphite-moderated, gas-cooled, Calder Hall type with an output of 150 Mw(e).

Specifications have been issued to: General Electric–Simon Carves Atomic Energy Group; A.E.I.–John Thompson Nuclear Energy Group; and the English Electric–Babcock and Wilcox–Taylor Woodrow Group.

Daigoro Yasukawa, spokesman for the Japan Atomic Power Co., said the contract will call for construction of a complete nuclear power station. The contractor will be responsible for the safe working of the reactor for a "certain" period after it comes into operation. Teams of Japanese technicians will be sent to Britain for training.

Yasukawa estimated construction would start in early 1959 and be completed by 1963 at Tokai, about 70 miles north-east of Tokyo. He said he could give no estimate of the cost.

Some re-designing will be necessary to assure safety during earthquakes.

Since January 18 a negotiating committee of Japan Atomic Power Co. has been visiting the sites in Britain where atomic power stations are presently under construction. Some industry observers, noting the number of visits the Japanese party has made to the Berkeley project, believe the A.E.I–John Thompson group may have the edge on its rivals. A spokesman for A.E.I.–John Thompson pointed out, however, that this may be due to the project's being further advanced than the others. The spokesman told NUCLEONICS its proposed design would be more advanced than that of the Berkeley atomic power station, yet would "probably be the simplest submitted."

Stone and Webster Buys Walter Kidde Nuclear Labs

Stone & Webster, a leading architect-engineering firm in the field, consolidated its position by purchase from Walter Kidde & Co. Nuclear Laboratories, Inc.—renamed Associated Nucleonics, Inc. Price was not disclosed. Wilbur E. Kelley, president of WKNL, remains as president of Associated Nucleonics, with T. Cortlandt Williams, S & W president, as board chairman.

Euratom Reactor Plan To Be Ready by June

A proposed timetable for the building of power reactors in the six Euratom countries will be presented to the group in June, a member of Euratom's Atomic Energy Commission disclosed last month. Enrico Medi, vice chairman, said the Commission has $215 million to pump into a reactor program.

On a visit to the U. S., he indicated the Commission was anxious to get started on both a power program and a physical research center (presumably at the site of Euratom headquarters to be selected in June from among Strasburg, Paris, Brussels, and Luxemburg).

The Commission, he said, will have a free hand to spend its power fund—loans and subsidies—in conjunction with World Bank or Export-Import Bank loans, or in any way it will produce the best results.

A U. S.-Euratom working party has begun the spadework for a joint, 1-million Kw reactor program for the Euratom countries. Euratom President Louis Armand plans an April visit in the U. S. for high-level talks.

PWR on utility duty; reactor's stability gratifying

At 8 a.m. Monday, February 25, the Shippingport Atomic Station went critical and to full power for the third time. It will do service for five of the next six weeks as a regular, peak-load station in the Duquesne Light Co. grid during scheduled maintenance on units at Elrama. Experience to date with PWR (NU, Jan. '58, 23, 68) has shown that this, this nation's first large-scale nuclear power station—like its smaller predecessors: APPR (NU, May '57, 26), EBWR (July '57, 60), VBWR, (Feb. '58, *facing* 76)—is remarkably stable under load changes. On Dec. 28, the entire 67-Mw (gross) load was dropped instantaneously when the turbine throttle valves tripped: the reactor followed, by temperature coefficient—the rod settings never moved; normal temperature and pressure were recovered at once, and immediate resumption of power output was limited only by synchronization of the generator. Bugs so far have been minor: a turbine governor valve broke and has been replaced; two (of 10,000) heat-exchanger tubes are leaking and will be removed while PWR operates, as intended, on three of its four loops. Meanwhile AEC and Duquesne are studying how the reactor performs under varying loads, and are completing plans for a later testing period, starting April, in which design operating conditions will be exceeded to determine the plant's real limits.

GE, ACF in contest for Elk River

General Electric and ACF Industries are locked in a spirited struggle over their proposals to AEC to build the Elk River boiling water reactor (NU, Nov. '57, 19). AEC's reactor division had tentatively decided in mid-February to recommend one of the two for approval by the Commission itself, but has since reconsidered, upsetting plans to announce the winner by March 1.

Italian reactor job hits snag

Owing to domestic, financial and other circumstances, Italy may retrench from four to three major power reactor projects, and one U. S. project is in some doubt. AGIP Nucleare's order in Britain for a Calder-type (NU, Dec. '57, 17) is apparently being transferred to SIMEA for construction near Rome, and SIMEA's contract with Vitro Engineering is being taken up by AGIP (NU, Sept. '57, 28). Whether Vitro's project reaches the construction phase is problematical, and may depend on the results of the Italian elections in May; in the meantime, Vitro is proceeding with its preliminary engineering study on plant definition and costs.

Democrats Seek Outer Space Policy Control for AEC

Under the glamorous spell of nuclear rocketry, the government adversaries over nuclear power policy declared a narrow but clear truce last month to present a bipartisan appeal for a major Atomic Energy Commission role in the conquest of outer space.

In an inspired atmosphere of sweetness and light, AEC Chairman Strauss and Congressional Democrats Albert Gore, Clinton P. Anderson and Chet Holifield released from the AEC/Air Force kennel Rover, Pluto and Snap, projects representing a broad effort to perfect nuclear propulsion for rockets and ramjets.

Meanwhile AEC and the Air Force announced new contracts for work in nuclear rocketry. Rocketdyne, a sister division of Atomics International in the North American Aviation Inc. family, got an Air Force study and research contract for development of a nuclear rocket engine—an extension of work underway at NAA in this field for some years. S. V. Gunn will be Rocketdyne project engineer for the work. And AEC extended its contract with the Boston firm of Edgerton, Germeshausen & Grier, calling on EG&G to "install and operate some of the control and measuring systems planned for use in the testing of nuclear reactors which may lead to development of nuclear rocket propulsion system." Tests will be conducted at AEC's Nevada test site.

A 90-minute hearing of the Joint Committee's Special Subcommittee on Outer Space Propulsion, headed by Senator Anderson, showed that AEC has and probably will retain responsibility for development of propulsion and auxiliary reactors, regardless of the outcome of the current controversy on space responsibility within Congress and the Executive Branch.

The hearing also produced the first unclassified discussion of Projects Rover, Pluto and Snap, plus a fourth, unnamed project covering ionic propulsion for mobility and maneuverability of a vehicle already thrust beyond the orbital pull of earth by a nuclear or chemical rocket. All four projects involve fission heat:

Rover—Development of a nuclear rocket of great thrust to lift heavy loads into outer space.

Pluto—Development of a nuclear ramjet aircraft.

Snap—Development of Secondary Nuclear Auxiliary Power for satellites and space vehicles.

Ionic Propulsion—Development of a nuclear power plant to provide a long-term energy supply for conversion to ionic thrust in outer space. An ion-propelled space vehicle would be the last stage of a rocket based on nuclear or chemical propulsion (see figure).

As with the nuclear navy and air force, the job of wedding perfected propulsion to the corresponding rocket frames and components is a joint one of AEC and the military. Admiral Hyman Rickover wears military and AEC hats for the Navy and Maj. Gen. D. J. Keirn is the corresponding chargé for nuclear aircraft. Col. Jack Armstrong, deputy to Keirn, is the "two-hat man" for Rover, Pluto, Snap and ionic propulsion.

Success Assured

Armstrong views the nuclear rocket as assured. He feels the problems are less formidable than those of the atom and hydrogen bombs, principally because of the technology available from these and other nuclear accomplishments and because "there are fewer uncertainties involved in nuclear propulsion." He told the Anderson subcommittee he would be the first to emphasize "it is not an easy job." But he also commented:

"If I did not think it was possible, obviously I would quit."

Subcommittee chairman Anderson called the February hearing for two major reasons: To publicize AEC's prospective contribution to rocketry and to make a strong play for giving AEC complete control of outer space activities in the Administration (under JCAE jurisdiction).

On the first, the hearing showed clearly that AEC, in cooperation with the Pentagon and other government agencies, has much to contribute.

On the second, where nothing is clear-cut, President Eisenhower has asked his Scientific Advisory Committee to recommend the best course of administrative action and Congress has moved to create its own special outer space committees.

Meanwhile, JCAE will continue to exercise its jurisdiction over nuclear space developments.

In this dramatic situation, Strauss and Armstrong appeared before the Anderson subcommittee to talk rocketry nucleonics. They were asked in advance to discuss current space programs, advanced concepts, comparative merits of chemical and nuclear propulsion, need for more money, availability of AEC facilities for work in this field and type of federal agency best suited to the task of conquering outer space.

Strauss' Views

Strauss' comments on these subjects:

- Current programs are Rover, Snap and ionic propulsion (Pluto is basically non-space, though it may have something to contribute).
- It is early in nuclear rocket development to be making accurate comparisons with chemical propulsion "and we have, of course, not yet proven that a nuclear system will, indeed, work." On the assumption that nuclear systems will work, however, "it appears that nuclear systems would be very attractive, particularly where large payloads in space travel are concerned."
- No "crash" acceleration of Rover and Snap is feasible for technical reasons but it might be worth the "big risk" to go ahead with Air Force spending "of large sums of money" on the development of nonnuclear components for the rocket "so that we would be off to a running start with the reactor when it has proved feasible." AEC has asked a $10.5-million increase in rocket spending in fiscal 1959.
- The Los Alamos and Livermore Laboratories, with prime responsibility in this field, could not significantly increase their efforts without impairing their weapons work, also their prime responsibility. The other AEC labs could play a larger part in the program if it were speeded up, he said.

Assuming a decision to go ahead with the Air Force's frame and component development, Strauss said, the necessary support facilities are already in existence "to a large extent," either in or out of AEC, "but not all that would be necessary."

- Because of the study ordered by the President on executive organization, Strauss could not comment on the best-suited type of agency.

Armstrong took the subcommittee a little deeper than Strauss—on a "personal opinion" basis—into the

nuclear-vs-chemical question. He viewed the nuclear rocket as simpler, because it would substitute single-stage for multi-stage vehicles; as lighter, because it would not require an oxidant; and as more powerful, because the thrust of an equivalent weight of a nuclear rocket would be upwards of 2–4 times the thrust of the best known chemically-fueled rocket.

"So," he explained, "if you accept the premise that the nuclear rocket, if successful, weighs less in its deadweight than a chemical rocket . . . and produces a thrust which is considerably greater, then I think I would rest my case that the payload or the distance which you can take it is obviously larger."

Once in outer space, Armstrong pointed out, the amount of thrust required "is very, very small."

"Therefore," he offered, "you can attack this from another viewpoint. That is to have a very, very small mass of material accelerated to an extremely high velocity. This is where the ionic propulsion scheme fits in. . . . "

"But this is going to require a major breakthrough . . . because the weight of the machinery to convert heat into electricity—and electricity is a must in ionic propulsion—is an extremely heavy thing."

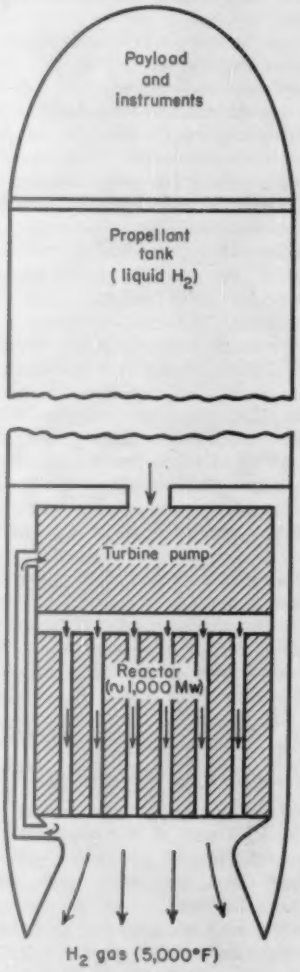
A nuclear source for this electrical energy is the most obvious, Armstrong contended, because of a reactor's ability to supply a continuing amount to the ion source and accompanying ion accelerator over a lengthy period.

"If you want electrical energy out in space for a long time, I don't know of any other way of getting it other than nuclear because any thing (based on) batteries or engines is obviously not going to run but a very short time."

A total of four federal agencies are working toward perfection of the ionic propulsion concept—AEC, the Air Force, the National Advisory Committee for Aeronautics and the National Science Foundation.

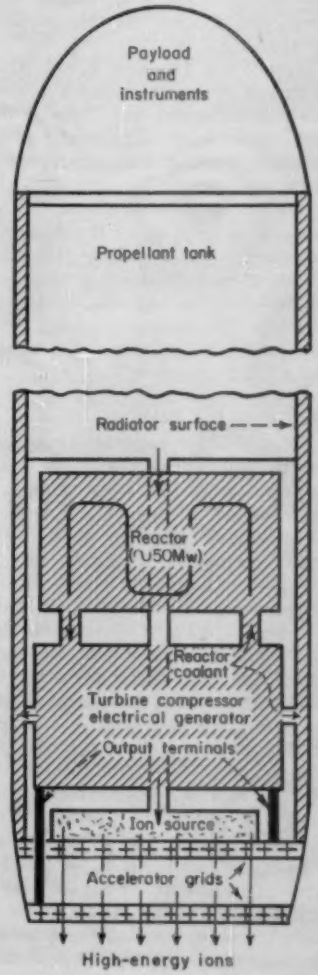
Armstrong told NUCLEONICS that "an awful lot" of firms have indicated interest in the Rover project, including a number doing some research-development work of their own. The only private interests under government contract on the nuclear rocket, however, are the University of California (contract operator of Los Alamos and Livermore Laboratories for AEC), Aerojet General, Rocketdyne and Edgerton, Germeshausen & Grier.

How Nuclear Rockets Might Work



A LARGE single-stage rocket (left) is powered by a solid-fuel-element reactor that heats hydrogen propellant to high temperatures to provide thrust. Unlike a chemical rocket, the nuclear version has no theoretical limit on the propellant exhaust temperature and is not forced to carry high-molecular-weight oxidizers such as liquid oxygen or flourine. This means that a nuclear rocket would have a burnout velocity at least twice that of the best possible chemical rocket for the same size and payload. A major problem is the engineering of a reactor core structure capable of withstanding the high temperatures necessary. Nuclear rockets could be used to lift payloads into orbit or provide complete escape—tasks impossible for single-stage chemical rockets. A typical design would weigh 100,000–200,000 lb, produce about ½-million lb thrust and use a 1,000–2,000-Mw(th) reactor.

A much smaller reactor (right) powers an ion-propulsion rocket. Fission heat drives a turbogenerator to produce electricity. The generator maintains a high voltage across the parallel grids which accelerate ionized fuel atoms to enormous exhaust velocities. Thus the ion-propulsion rocket extracts up to 50× more impulse than a conventional rocket from the same amount of fuel; the cumbersome equipment required to generate electricity from heat, however, imposes a thrust-to-weight ratio ~1000× smaller. As ion-propulsion rockets can best provide a small thrust for a long time, they are ideal for travel in free space after gravitational escape. A 200,000-lb ion-propulsion rocket using a 50 Mw(th) reactor could, after 6 months of acceleration, reach a velocity of about 100,000 mph.



Boost in Research Funds Sought by Scientists, JCAE

The science-minded 85th Congress, displaying a sharp interest in improving America's scientific position, is almost certain to dump a batch of extra money into the lap of the Atomic Energy Commission for basic research.

The Joint Committee on Atomic Energy last month took the unusual step of calling in 50 of the nation's top scientists for a two-week-long, technical briefing on U. S. progress —and needs—in basic research.

Rep. Melvin Price (D-Ill.), the subcommittee chairman stated his conviction that "lack of sufficient funds and inadequate facilities are among the chief obstacles to continued progress in our physical research program, both in the civilian and defense fields." He proposes that spending for basic research be increased by at least 50%, and is confident JCAE will recommend a big stepup in the $71.5-million currently being spent for this purpose by the AEC.

Rep. Carl Durham (D-N. C.), chairman of the full committee, says the hearing series was "one of the best and most important on a scientific subject I've seen in my years in Congress."

A procession of witnesses, led by Alan T. Waterman of the National Science Foundation, flatly called for an increase of 50–100% in spending for basic atomic research as soon as possible. Waterman warned that "our technological future lies in the lap of basic research."

We—and the Russians

Several of the scientists agree that the U. S. still leads the Soviet union in basic research, but that this lead may be lost unless the U. S. does something to improve the quality and quantity of scientific teaching in high schools, and increases government support for basic research.

Luiz W. Alvarez of the Univ. of California says the Russians are very competent, but thus far are mostly doing work which has already been done in other countries. "I expect that in the next few years we will see them branching into areas of physics that we have not been in yet," he predicts.

Isador I. Rabi, 1944 Nobel prize-winning chemist from Columbia Univ., agrees that we are still "way out in front" of the Soviet Union in basic research, but that the Russians are coming along rapidly and may very well pass us unless something is done about the failure of secondary schools to offer students proper grounding in science.

"I suspect the American people are more ready to support adequate research than the Budget Bureau is willing to believe," Rabi concluded.

The hearings covered a wide range: nuclear chemistry, radiation and hot atom chemistry, high temperature problems, ion exchange, free radicals studies, high energy physics, high energy accelerators and use of computers.

Fusion Progress

Highlight, however, was a review of progress and problems on Project Sherwood—the effort to harness thermonuclear power.

Melvin Gottlieb, chief of thermonuclear experimentation at Princeton, testified that the requested $800,000 increase in Sherwood's budget for the next fiscal year should allow completion of the C-Stellarator at Princeton by mid-1959 —two years earlier than originally planned. It will be used to put a very strong magnetic field outside an eight-inch pinch tube—about three times larger than tubes now in use—in efforts to further confine and stabilize the plasma.

Price Summarizes

As the hearings ended, Chairman Price said the testimony convinced him of two prime needs:

- The 50% increase in spending for basic research by government, industry and the universities.
- Government stimulation of more scientific education in the secondary schools. Price already has a bill pending which would provide outright cash grants of $500 for any high school graduate passing a mathematics achievement test.

AEC's basic research expenditures have climbed from $21-million in 1948 to $71.5-million in the current year (not including thermonuclear work). AEC plans no increase, although officials say the matter is under continuous review and "we can reprogram more if we find that it's needed."

Price, obviously dissatisfied with AEC's stand, says the nation's total basic research effort must be increased by 50%. Most of the increase must come from the government, he says; accordingly, government expenditures might well be doubled. He is confident that the Joint Committee will back him up on this.

Uranium Industry Seeks Congress' Help in Crisis

The government-born and -bred uranium industry, suffering its first attack of growing pains, turned to Congress last month for help in selling more ore and oxide.

The combination of a levelling-off in AEC purchases and an insubstantial commercial market left the industry with a high rate of exploration and development but no corresponding demand (NU, Jan. '58). To support the industry while it awaits the growth of an industrial market, Congress was asked to consider at least three possible moves:

1. Authorize U. S. uranium producers to sell in the commercial world market.
2. Inaugurate a stockpile purchase program beyond what is needed for normal weapons and non-weapons consumption.
3. Limit AEC purchases from foreign suppliers.
4. Require AEC to reconsider its present domestic policy.

The industry's first real crisis was something of an anomaly. Most producers and millers (who convert U ore to oxide) were doing excellent business with the AEC at good prices and under long-term guarantees. Others, however—particularly in areas of recent discoveries like Wyoming and Colorado—were complaining that AEC had frozen them out of the market by its October order virtually halting mill construction.

From an industry point of view, the October order has boiled down into a fight by the "outs" to enter the AEC purchase program alongside the "ins." From the AEC point of view, buttressed chiefly by the Budget Bureau, uranium purchase money has reached a ceiling. AEC's new budget of $2.4-billion (fiscal year 1959) allocates nearly $650-million or 27 percent, for purchase of U, according to Jesse Johnson, AEC's chief for raw materials. By 1960 and 1961, he said, spending will run "well in excess of $700-million."

"As a result of the tremendous

New Mill for Wyoming

A 1,000-ton/day uranium mill for the Gas Hills area of Wyoming has been proposed to AEC jointly by Vitro Minerals Corp. and Atlas Corp. More than 1.5-million tons of U-ore reserves in the area were shown by a $2.25-million exploration program.

increase in domestic ore reserves during the past three years and the prospects of further increases," he told the National Western Mining Conference, "a policy of unlimited purchases would lead to serious overproduction and a greatly increased uranium budget."

Johnson hinted that increased spending for U-buying might jeopardize the AEC spending rate for development of reactors the industry must look to for its best market.

"The atomic power program is most important to the uranium industry," he pointed out, "for its future depends upon the development of reactors that can produce competitive power. . . . It is necessary to limit the funds for each essential program to those which can be used effectively.

"In the case of uranium, this means that deliveries and requirements should be in approximate balance. That balance will be achieved by deliveries under existing domestic and foreign commitments."

Johnson readily declared his concern "over the problems of those who already have developed ore at substantial expense and who as yet may have no adequate market for their ore." His office is conducting a survey on the dual necessity for solving these problems and encouraging enough exploration and development over the next several years to support the heavy demand anticipated in the '60's.

Johnson was among several conference speakers who warned that exploration and development efforts must not come to a halt.

"The long-term outlook," he said, "is for expanding production to meet the requirements for atomic power. Continuing exploration will be needed to assure ore reserves for this future expansion and to provide the basis for huge capital investments in atomic power plants.

"In my opinion, the minimum exploration and development rate should be one that would maintain our domestic ore reserves at approximately the present level (75,000,000 tons). On the basis of the 1959 ore production rate, this would mean developing about 7,000,000 tons of ore a year (to give a reserves-consumption ratio about 10–1)."

A subcommittee of the Joint Committee on Atomic Energy, headed by Sen. Albert Gore (D.-Tenn.), has scheduled the first JCAE study of the U-industry, later this year.

Navy Rushes Ballistic Missile Atom Submarines; Seeks A-Destroyer, 5 More Subs for '59 Program

Acting with jet-age speed, the Navy assigned three new nuclear ballistic-missile-firing submarines to shipyards for construction only three days after Congress approved a supplemental appropriation for them. The first two will be built at the Electric Boat division of General Dynamics—the Groton, Conn., shipyard that has built or is building the first of each of the seven earlier classes of A-subs starting with *Nautilus*. The third FBM (for Fleet Ballistic Missile) submarine will be built by Mare Island Naval Shipyard, Vallejo, Calif.

A $13-million contract went at the same time to General Dynamics for preparation of construction plans and calculations on the FBM-type sub. An $18.63-million Navy contract was awarded Westinghouse for reactor components for the three subs, and a $6.36-million order went to General Electric for propulsion machinery (NU, Feb. '58, 28).

Congress had voted $296-million for the first three units of this new class. The first vessel is expected to cost $105–110-million, the next two $85–90-million each. And the Navy has asked that the 1958 shipbuilding program be further expanded by another supplemental appropriation to allow for six additional FBM subs, for a total of nine.

Four nuclear-propelled submarines that will fire the Regulus guided missile are already under construction. The FBM subs, as the name implies, will be armed with a ballistic missile—Polaris, a 1,500-mile-range weapon with a thermonuclear warhead.

The first three FBM submarines will be the world's largest at 5,600 tons, 380 ft long, 33 ft in beam—shading the 5,450-ton *Triton*, a two-reactor radar picket submarine now building at Groton. (Previous undersea recordholders were France's plane-packing *Surcouf*, 2,880 tons, sunk in 1942, and Japan's three late-World War II monsters of the I-400 class, 5,223 tons.)

Big though they are, the FBM subs will have the revolutionary *Albacore* or whale-shaped hull design that will endow it with tremendous underwater speed. (The first of seven *Albacore*-hull subs with nuclear propulsion—*Skipjack*—will be launched at Groton this spring. It will be "conventionally" armed—with torpedoes.) Navy officials disclosed in Washington that the FBM subs will be able to carry "more than 10" of the 30-ft solid-fuel Polaris missiles—some reports said "up to 16." They will be equipped with the revolutionary SINS (ship's inertial navigation system) whose gyroscopes will permit the vessels to determine their exact position when firing their missiles submerged, without reference to celestial bodies.

The first of the FBM subs are scheduled to be delivered in 1960, coinciding with the time Polaris is due to go into quantity production.

Meanwhile Lockheed Missile Systems announced start of an urgent building program on a multi-million-dollar Polaris ground-testing station in the Santa Cruz mountains south of San Francisco, to accelerate Polaris development. The remote facility, comprising a complex of concrete-and-steel test stands, will permit static testing of missile parts under flight-like conditions of heat and vibration; the rocket engines will actually be fired, but no missiles will be launched.

1959 Shipbuilding Program

Appearing before the House Armed Services Committee, Chief of Naval Operations Arleigh A. Burke disclosed that in its fiscal-1959 shipbuilding program, the Navy had included (and was asking funds for) the long-awaited nuclear destroyer and five further A-subs, one a missile-launcher, the other four attack or anti-submarine types.

Late in the month *Skate* set a 203-hours-to-England record for A-subs, steaming 2,828 of 3,161 mi submerged.

And Now: Submarine Tanker

Maritime Administration has given General Dynamics a $25,000 feasibility study contract on a huge, speedy submarine tanker with nuclear power. It contemplates a 60,000–100,000-ton, *Albacore*-shaped tanker doing 35 knots at a shallow 100 ft below the surface. If the study warrants, MA would ask Congress for the $30-million estimated cost of a prototype. A surface tanker of equal capacity would cost $20–25-million, do only 18 knots, require a larger crew. The sub tanker would also be immune to delays due to bad weather, hull damage due to buffeting by heavy seas.

AEC Seen Anxious to Reduce Atom Regulatory Task; Ohio Coordinator Predicts Enlarged State Role Soon

"The states may have to assume a host of new governmental responsibilities (on atomic energy) sooner than they anticipate—responsibilities which for the most part are presently pre-empted by the federal government."

This is the prediction of William H. Eells, 36-year-old pioneer in an area of considerable interest to the nuclear industry: state and local jurisdiction over commercial application of the atom.

Coordinator of atomic development activities in the state of Ohio since Oct. 1, Eells has been catapulted into the center of a transitory brew which tastes of a federal government attempt to back away from its regulatory role and a state government move into the regulatory and promotional picture.

The brew's eventual appeal to nuclear businessmen depends to a substantial extent upon Eells and a handful of men like him who have been assigned weighty state responsibility for atomic regulation and promotion.

Eells' views and activities are particularly significant because he is the first officer in any state asked to take full-time authority over the peaceful atom, and to be given a cabinet-level chair from which to handle the job. He, more than any other man in the Ohio government, will shape the state's regulatory laws and its public attitude toward nuclear industrialists. What Ohio does, in turn, will have an important bearing on the procedures eventually adopted by other state governments (more than 30 states have some degree of activity).

"It is important," he told NUCLEONICS, "for the states to make two points their guide: (1) to do as much as possible to encourage peacetime development of atomic energy for the benefit of the public and (2) to do everything possible to guard against hazards which are an outgrowth.

"There is no question in my mind that we must go all the way to protect the public health and safety.

"However, this is not just a public health problem, nor is it just an industrial relations or insurance problem, and this is where a coordinator definitely fits into the picture—for it is a combination of all these and other (problems) which must be solved."

Eells shares the view of most other leaders in the field that existing state agencies can assume the duties in nuclear regulation and promotion which they already exercise in dealing with other industries. In this respect, Ohio's atomic energy law, signed by Governor C. William O'Neill last June, has made a major contribution to easy transition from federal to state authority, Eells asserts.

"We feel, first," he explains, "that this law is a positive step for the present and certainly for Ohio's future. It is of help to the growth of industry, medicine and agriculture and, at the same time, it reassures the public as to safety and health implications.

"Second, it gives legal sanction in the field without establishing any vast regulatory agency. I have interpreted this office as an Ohio clearing house on peacetime atomic energy matters, and I think the law lends to a favorable and receptive climate for development by going through existing channels or departments already in business.

"Third, it puts 'teeth' into atomic problems by placing the position of coordinator (Eells) at a high level in state government as a 'deputy' of the governor. Governor O'Neill has again evidenced his support of this legislation by having [Eells] take part in weekly cabinet meetings."

Eells sees the Atomic Energy Commission as overburdened with regulatory chores and anxious to abdicate as many of these responsibilities as it safely and smoothly can in favor of the states. Among other things, he bases this opinion on a several-hour interview with AEC chairman Strauss in January, and the recent moves by AEC and others to get Congressional sanction for reduced federal jurisdiction over the new industry.

Federal Legislation

AEC has proposed federal legislation which would permit the states to adopt their own radiation standards and other measures so long as the regulation of nuclear firms is not watered-down in the process. AEC would retain its licensing function. Other bills to put the states into the regulatory business (and concurrently ease AEC out of it) have been suggested by the chairman and vice chairman of the Joint Committee on Atomic Energy, Rep. Carl Durham and Sen. Clinton P. Anderson, respectively.

Moreover, JCAE has informally indicated it will conduct public hearings on the entire federal-state issue this year—its first real look at the problem.

From these and other signs, Eells concludes that "the states must speed up their activities to be ready for new administrative functions."

"If we expect to encourage the development of the peacetime uses of the atom," he warns, "the states must have a healthy, receptive climate made possible by the establishment of responsible, orderly government procedures which can readily adjust to the new demands in an atomic era."

Eells has expended considerable effort in counselling state department heads against moving too swiftly into the nuclear field with legislative proposals and regulations that might prove inadequate or overadequate.

"I think, as public officials in this field," he advises his cabinet colleagues, "we must move with caution in adopting new codes and legislation. (They) must be built . . . on actual experience."

Finally, Eells feels strongly that constant contact with the public—"the educational-public information phase"—is a major area of his activity.

Major Provisions of Ohio's Atomic Energy Law

- **Directs the agencies of health, industrial relations, highways, insurance, natural resources, public utilities and others to "initiate and pursue" studies on legislation and regulations needed for adequate supervision of nuclear activities.**
- **Directs the governor to appoint a full-time deputy to coordinate "the development and regulatory activities of the state government relating to the industrial and commercial uses of atomic energy," in liaison with interested state agencies, other states, federal authorities, and the public.**
- **Creates an 11-member atomic energy advisory board to backstop the coordinator. Its membership includes the coordinator, one person representing each of labor and management, a medical doctor, two nuclear scientists, and five with unspecified qualifications.**

Reactor News

GE COMPLETES NEW FUEL PLANT

A $1.5-million addition to its nuclear fuel element manufacturing facilities has been completed by General Electric at San Jose, Calif. The 32,000-sq ft plant complements an earlier $1-million, 15,000-sq ft building that will now be used entirely for making research reactor elements and for studying improved element designs. The new plant contains $1-million worth of equipment to make rod-type elements of uranium-oxide pellets in stainless-steel or zirconium tubes. It includes uranium-powder-blending machinery, pelletizing presses, baking ovens to harden the pellets at up to 3,000° F, and tube-loading and welding equipment. The plant can make 300,000 pellets, 0.5-in. long × 0.5-in. dia, per month, will start by making the 3.5-million pellets needed for the Dresden Station's first charge.

PURR WORK STARTING

AEC issued bids last month for construction on the Plutonium Recycle Reactor to be built at Hanford Works (NU, Jan. '58, 62). The work will include a steel containment shell 80 ft dia × 121 ft high, 46 ft below grade; installation of a circular bridge crane, air conditioning and ventilation, adjacent storage facilities, etc. The work is to be done in 14 months. A separate bid invitation covers installation within three months of piping, roads, fencing, a disposal pit, a parking area and other utilities.

NEW LARGER TURBINE FOR VALLECITOS ?

Pacific Gas & Electric Co. is "giving very serious thought" to replacing its 5-Mw(e) turbogenerator at the Vallecitos boiling reactor with a larger one, a P.G.&E. engineer told the *Oakland Tribune*. Since the reactor went to higher power (NU, Feb. '58, 26), 2.5-Mw(e) has been dumped to condensers. The present turbine cost ~$570,000. The reactor may be capable of as much as 25 Mw(e), five times design power, according to its designer and manager, Samuel Untermyer II; "it is still too soon to say what the upper limit" of its capacity may be, he adds.

TELLER CO. GETS TREAT CONTRACT

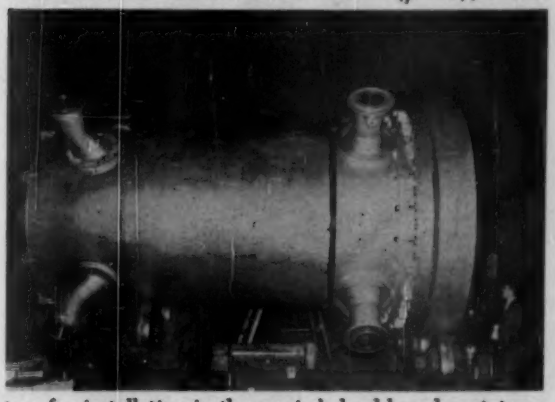
With a low bid of $334,716—well below AEC's final estimate of $475,000—Teller Construction Co. of Portland, Ore., won a contract to build the non-nuclear portion of TREAT—the Transient Reactor Test facility at the Idaho reactor testing station. (NU, Jan. '57, 26). Nine other firms bid.

CORNELL PLANS 2-IN-1 TEACHING REACTOR

Cornell Univ. has developed a unique design for a two-core teaching reactor, and has asked AEC for a construction permit, NUCLEONICS learns. The $600,000 unit would consist of a 10-kw pool unit as a neutron source, and a separate 10-watt core for reactor physics work, operating alternately from a single console. The former would resemble the Naval Research Lab pool but with the core fixed, not on a moving bridge; the latter would be like the Brookhaven critical assembly. A $600,000 building housing them would contain a gamma irradiation facility, student labs, counting rooms. Vitro has been collaborating on detailed plans.

A-CARRIER *ENTERPRISE* BEGUN

The keel was laid Feb. 4, in a graving dock of the Newport News Shipbuilding and Drydock Co., for the Navy's mammoth eight-reactor nuclear aircraft carrier named *Enterprise*, after the heroic flattop of World War II. Meanwhile this 100-ton reactor vessels (*photo*), one of



two for installation in the carrier's land-based prototype, was shipped from Foster Wheeler's Mountaintop, Pa., shops to the Idaho reactor testing station (NU, Sept. '57, 26). Exceeded in size only by the Shippingport vessel (NU, Dec. '56, 26), the vessel is over 19 ft long, 105 in. dia; its flange is 18 in. thick, 137 in. dia. The shell is formed of 7-in.-thick manganese-molybdenum alloy steel lined with stainless. Meanwhile on the political front in Washington, Rep. Clarence Cannon (D.-Mo.), chairman of the House Appropriations Committee, failed in two moves to kill the carrier project, but succeeded in quashing *Enterprise's* sistership, which was envisioned by the Navy as second of a class of six. Cannon wants to see the money spent on submarines. The Navy told his committee that killing the $314-million *Enterprise* would cost $80–100-million in cancellation fees and expenditures already made.

NEW *SEAWOLF* REACTOR CONTRACT

The Navy has asked Congress for $20-million to pull out *Seawolf's* sodium-cooled intermediate-neutron reactor and replace it with a pressurized water system now standard for all Navy A-ships (NU, Feb. '57, 26). Westinghouse got a $750,000 contract for the reactor.

MICH. STATE PLANS REACTOR, CYCLOTRON

Michigan State University has asked the state legislature for $2-million to fund a research reactor and $1-million to build a heavy particle cyclotron. The cyclotron, with practical priority over the reactor project, is scheduled for a construction start this year. It is a two-stage project designed to accelerate heavy particles and protons initially, and particles up to the weight of argon eventually (40–50-Mev).

MARTIN WINS SPERT-2 FUEL CONTRACT

The Martin Co. won over six other firms in bidding to fabricate 30 uranium-aluminum control-rod sections, 68 fuel assemblies and 750 fuel plates for AEC's power excursion test reactor (SPERT-2) at Idaho. Martin's low bid calls for ten 17-plate control rod sections at $486.72 each; ten 8-plate sections at $350.30; ten 5-plate sections at $299.20; 68 fuel assemblies at $473.42; and 750 fuel plates at $10.20 each. Other bidders were Clevite, D. E. Makepeace, General Electric, M&C Nuclear, Sylvania, and Westinghouse. Low bid total was $51,204.76.

ROUNDUP

World News

Compulsory Insurance in Britain

A bill now being prepared for Parliament would require compulsory inspection and insurance of all British reactors. All reactor owners would have to be licensed by the government and be able to pay compensation up to £5-million ($14-million) for any one incident—a figure held by the government to be "much more than adequate" to cover any foreseeable risk per incident. British insurance companies have told the government they are ready to give this amount of coverage, Commons was told. So far there is only one privately-owned reactor in Britain, the "Merlin" swimming-pool being built by Associated Electrical Industries at its Aldermaston research center; the big power stations are all owned and operated either by the Atomic Energy Authority or the nationalized electricity boards.

Insurance Pool in France

100 insurance firms—80 French and 20 foreign—have consolidated to cover nuclear accidents in France. The group, officially called "The Pool," has organized a system of mutual reinsurance or risk-dispersion. Maximum coverage offered is slightly more than $4-million. Main type of policy now issued is on use of radioisotopes in hospitals and research labs.

Europe-wide Liability Code Studies

Common European regulations on third party liability in the nuclear field are under study by a new experts' group set up by the Organization for European Economic Cooperation. Results may be embodied in an international convention harmonizing atomic insurance legislation in the 17 OEEC countries.

RWE Still Seeking Plant Bids

Offers for building a 250-Mw(e) power reactor are expected by April, Director Heinrich Schöller told the annual stockholders' meeting of RWE, West Germany's biggest utility. RWE had earlier arranged purchase of an AMF Atomics–Mitchell Engineering 15 Mw(e) boiling reactor, but the deal fell through together with AMF's negotiations for a similar reactor at Elk River, Minn. (NU, Nov. '57, 19; Feb. '58, 21.) Schöller said RWE has been negotiating since last June with four British firms for a big gas-cooled reactor, whose cost might run $72–95-million. However if the supplier cannot guarantee operating cost competitive with an equivalent coal plant—a guarantee RWE doubts it will get—the utility plans to build a 10–15-Mw(e) reactor for $7–9.5-million, to gain experience.

Agreement on Sweden's R4 Signed

An agreement for collaboration in building the R4 reactor, to power the Swedish State Power Board's "Eve" nuclear central station, has been signed between the joint government-industry atomic development company Atomenerg, the electrical equipment manufacturer ASEA, and Nydqvist & Holm (NU, Dec. '57, 23). First step will be for the three to set up a working group to study suitable reactor types. The plant, Sweden's first large-scale A-power plant, is to be completed by 1964. It will be built underground, probably in a mountain on Lake Unden in west-central Sweden.

Cole Fills Top Agency Posts

Four deputy directors-general and 11 division directors of the International Atomic Energy Agency were named by Director General W. Sterling Cole in Vienna last month. Sworn in as his chiefs of staff were Paul R. Jolles of Switzerland, until recently executive secretary of the Agency's Preparatory Commission, as head of Administration, Secretariat and External Liaison department; Hubert de Laboulaye of France as head of Technical Operations dept.; V. V. Migulin of Russia as head of Training and Information dept.; and Henry Seligman of Britain as head of Research and Isotopes dept. Andrey I. Galagan of Russia was named Agency representative to the United Nations, and the following take over as directors of the Agency's operating divisions:

Mario E. G. Bancora, Argentina, Technical Supplies
John E. Cummins, Australia, Scientific & Technical Information
David Fischer, South Africa, External Liaison
Yoshio Fujioka, Japan, Isotopes
U. L. Gaswami, India, Economic & Technical Assistance
Karol Kraczkiewicz, Poland, Personnel
Joaquim da Costa Ribeiro, Brazil, Exchange & Training of Scientists
Antonio Rostagni, Italy, Research, Research Contracts & Labs
Josef Snizek, Czechoslovakia, Reactors
Donald G. Sullivan, U. S., General Services
G. W. Campbell Tait, Canada, Health, Safety & Waste Disposal

At a meeting of the Agency Board of Governors, U. S. delegate Robert McKinney announced a U. S. offer to make available cost-free 120 fellowships to students chosen by the Agency for study in the U. S., plus half the $250,000 Agency Fellowship Fund, and the services of 20–30 expert consultants.

Eurochemic Founders Prepare Building Start

Preparations for construction of a European chemical reprocessing plant begun at Belgium's nuclear center at Mol. The $12-million plant is being built by Eurochemic, a twelve-nation company set up under sponsorship of the Organization for European Economic Cooperation (NU, Jan. '58, 22).

Australia's First Reactor Critical

First low-power tests have been completed on HIFAR (High-Flux Australian Reactor), the first reactor Down Under, at Lucas Heights near Sydney (NU, Oct. '56, R7).

Research Center for Pisa University

Work will start this summer on a nuclear research center at San Piero a Grado, 4 mi SW of Pisa. To be built by the Univ. of Pisa, the Livorno naval academy, and other scientific groups, the center will have a 12–15-Mw pool-type materials testing reactor. Meanwhile the first two shipments of parts have arrived on site at Ispra for Italy's first research reactor.

A-Ship Advance in Norway

An association for joint financing of nuclear ship research has been founded by 19 Norwegian shipping companies. It signed a contract with the Norwegian Atomic Institute for a 2-yr, 1-million Kr. ($193,000)/yr, research program designed to develop nuclear merchant ship propulsion (NU, Nov. '57, 87).

South African U-Exports Still Rising

The value of South Africa's exports of atomic materials —mostly uranium—during the first 11 months of 1957 is announced at just over £46-million ($128.8-million), an increase of $32.2-million over the same period in 1956.

Iron Curtain Notes

Civilian nuclear submarines can be used for a broad range of peaceful purposes, according to Soviet scientists and submariners, including oceanographic research; penetration into the central Arctic and Antarctic under ice; high-speed transportation; year-round communications along the North Sea route; fishing and whaling; cable-laying; rescue work. . . . 140-million rubles (~$35-million) have been allocated by the Kremlin for a nuclear research center in Alma Ata, capital of the Kazakh S.S.R. A powerful research reactor, cyclotron, and 15 laboratories in as many fields will be provided at the center, to be commissioned in 1960. Part of an evident effort to develop—and harness—the Soviet Union's minorities, announcement of the Kazakhstan nuclear center follows others recently decreed for Uzbekistan (NU, Oct. '56, R8) and Georgia (Sept. '57, 31). . . . The Nuclear Physics Institute of the Czechoslovak Academy of Sciences has developed a reactor for use with heating plants in large towns. Design problems are also under attack for the first atomic power station, to be built in Slovakia . . . Poland and Russia signed an agreement in Moscow whereby the Soviet will aid the Poles in designing and building their second research and first power reactors. Aid will also be furnished on prospecting, mining and processing Polish uranium (NU, Nov. '57, 26); Polish U reserves were recently stated to be 300% greater than previously believed.

Power Station for India Nearer

According to Indian Minister for Planning Gulzarilal Nanda, the Planning Commission finally has agreed that India's AEC set up a 140-Mw(e) nuclear power station, probably in Bombay state. IAEC is reported to have located a suitable site for India's long-discussed first A-power plant near Ahmedabad, India's textile center on the edge of the Rajasthan desert and 1,500 mi from the nearest coalfields (NU, Feb. '56, 15; May '56, 142).

Holland: A Submarine, a Resignation

The Netherlands Minister of Defense has set up a working group to study construction of a nuclear submarine, expected to enter service in 1960. . . Prof. J. M. W. Milatz, managing director of the Netherlands Reactor Center, has tendered his resignation because of criticism leveled against the Center's lack of activity lately. The Center's board of directors is considering the move.

Power Division at A.E. of Canada

Atomic Energy of Canada Ltd. is setting up a Nuclear Power Plant division, to be responsible for both NPD, the 20-Mw(e) Nuclear Power Demonstration reactor, and the development program for a 200-Mw(e) scale-up. The division will be located in Toronto because of proximity to manufacturing facilities and shortage of office space at Chalk River, headquarters of A.E.C.L. Heading the new unit will be H. A. Smith, assistant general manager for engineering at Hydro Electric Power Commission of Ontario but on loan to A.E.C.L. for the past four years as chief of Nuclear Power branch at Chalk River.

Uranium Finds in Mideast

Iraq, Egypt and Sudan have all made discoveries of uranium deposits, government sources in the three countries report.

Finland Plans U-Export

Finland has "important" resources of uranium and may be exporting it by this summer. According to Managing Director Aarne Hollmen of Atomienergia Inc., a nuclear development firm founded by Finnish paper and electric power companies, samples taken in one area to a depth of 30 ft show 4–10% U content in the ore. Atomienergia intends to build a mill for uranium oxide, to be in production by end of 1959. The oxide would be exported in exchange for enriched U and nuclear plant machinery.

News in Brief

AEC Sponsors Research on Glass-Fiber Fuel

Rensselaer Polytechnic Institute has been granted $191,000 by AEC for further research by Paul Harteck and Seymour Dondes on the feasibility of using glass fibers containing uranium oxide as reactor fuel. The new fuel material first revealed in NUCLEONICS (NU, Aug. '57, 94), holds promise for high-temperature operation.

High Voltage Acquires Electronized Chemicals

A controlling interest in Electronized Chemicals Corp. of New York has been acquired by High Voltage Engineering Corp. The new subsidiary has been a pioneer in electron-processing research for over a decade.

Nuclear Engineering Dept. at MIT

Massachusetts Institute of Technology, a pioneer in atomic energy teaching, is establishing a Department of Nuclear Engineering under Manson Benedict. MIT has been offering nuclear engineering courses since 1952, in the Chemical Engineering department. The curriculum will include fusion. MIT is completing a $2.64-million high-flux tank-type research reactor, a heavy-water-moderated CP-S type.

Metal & Controls Set A-Sales Record

Record sales of $36-million were made in 1957 (as compared with $33.8-million in 1956) by Metals & Controls Corp., riding on Navy demands for nuclear fuel. The gains were chalked up in the face of declines in the company's appliance, automotive, aircraft and jewelry orders which caused a drop in net income from $2.4- to $1.5-million. Improved return in 1958 was forecast by President Carroll L. Wilson, who explained that nuclear work for the Navy in 1957 was "almost entirely on a cost-plus-fixed-fee basis," while a large part of increased nuclear fuel volume in 1958 is expected to be at a fixed price.

AEC Orders Texas Isotope Work Halted

Radiation Products Co. of Dallas has been ordered to cease all operations involving radioactive material, pending a public hearing on possible suspension or revocation of its license. The firm, licensed to possess up to 10 curies of cobalt-60 and 15 of cesium-137 for encapsulation and distribution to licensed users, is charged with having transferred at least two Co^{60} sources of one curie each to non-licensed persons.

ROUNDUP

AEC Seeks Tanker BWR, Second Core for Savannah

AEC has asked bids on a design engineering study on a boiling water reactor system to power a T-5 type tanker under construction at Ingalls Shipbuilding Co., Pascagoula, Miss. It is also seeking a second, back-up core for the reactor of *Savannah*, the first nuclear merchant ship. The first core is to be built by Babcock & Wilcox, prime contractor for the ship's propulsion plant. Some eight firms bid; at least two, eminently qualified, did not, NUCLEONICS learned, because they considered invitation information inadequate and confusing.

Schenley Enters Field, Buys Heavily Into RAI

Schenley Industries Inc. entered the atomic field last month with purchase of "a substantial stock interest" in Radiation Applications Inc. Schenley is the second of the big four in alcoholic beverages to do so—National Distillers, through its U.S.I. Chemicals subsidiary, has long been active as a zirconium producer. Schenley had earlier diversified into pharmaceuticals, toiletries, dyes and farm feeds. RAI has been engaged in consulting, testing, research and development for AEC and private firms, and markets a cobalt irradiation unit.

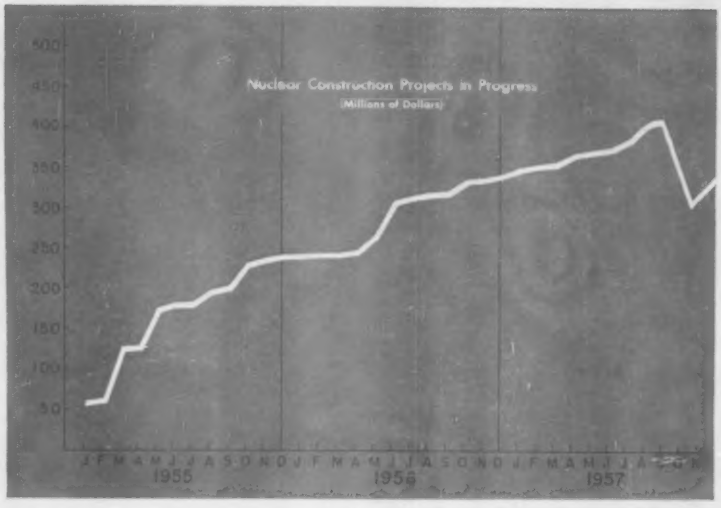
AEC Approves PAR Aid, Over Dissent by Graham

The Pennsylvania Advanced Reactor project bid for AEC research and construction aid (NU, Jan. '58, 28) was approved by AEC, 4–1, with Commissioner John S. Graham dissenting. In a written statement, Graham objected that PAR involves too many technical problems to be suitable for AEC approval at present —despite the fact that PAR project plans call for two more years of research before a decision is made whether or not to build the plant. AEC's intention to give financial aid must now be approved by the Joint Committee. At the "202" hearings last month, PAR's sponsors—Pennsylvania Power & Light Co. and Westinghouse—reported "substantial and encouraging progress."

Don Kallman Killed In Auto Accident in Italy

Donald A. Kallman, 35, nuclear economist and sales engineer for Babcock & Wilcox, was killed March 5, together with his wife, Nancy, in an automobile accident in southern Italy.

NUCLEONICS Statistics of the Month



	Latest month	Month ago	Year ago
Nuclear Contracts*—			
Contracts awarded for federal projects ($10³)	2,980	4,183	7,542
Proposed construction, privately-owned ($10³)	0	3,500	6,550
Contracts awarded, private work ($10³)	0	500	1,500
Backlog of private projects ($10⁶)	247	247	175
Access Permits†—			
Access permits issued	13	17	41
Total access permit holders	1,402	1,404	1,184
Isotope Use†—			
Applications for isotope use	465	438	447
Cumulative total of isotope users	3,469	3,392	3,738
Oak Ridge National Laboratory shipments	1,243	1,134	1,189
Public and private export shipments	91	222	98
Employment†—			
AEC employment	6,735	6,808	6,632
Construction and design contractors' employment	11,286	11,692	15,168
Total operating contractors' employment	99,073	97,195	93,810
Production workers	50,280	50,294	49,996
Research and development employees	42,736	40,741	37,944
Miscellaneous workers	6,057	6,160	5,900

	Operating	Building	Contracted
U. S.-built Reactors‡—			
Power, domestic	1	5	8
Power, for export	0	1	5
Power experiments and pilot plants	7	3	3
Military and naval	5	20	13
Research and test, domestic	41	26	38
Research and test, for export	7	14	4
Foreign-built Reactors‡—			
Power, domestic	4	24	12
Power, for export	0	0	2
Research and test, domestic	25	17	6
Research and test, for export	4	8	1

* From *Construction Daily*, a McGraw-Hill periodical † From AEC ‡ NUCLEONICS figures

New Instrument News

Operation and Selection of "RCLiac" Scaler-Analyzers

General Description

The "RCLiac" scaler-analyzers are innovations to nuclear data processing. Nuclear detector pulses are processed and quantized in total or in spectra.

Operation and Application

Two basic modes of operation yield extensive applications in the laboratory. Gross counting, the scaler mode of operation, affords events-per-interval-of-time or time-per-event analysis. Time intervals or event totals may be preset. Simple applications in this mode of operation are: half-life determination, pulsed reactor response, fast-neutron velocity distribution, and other similar studies. With the aid of an automatic sample changer, as many samples as there are channels can be counted, automatically.

The spectrometry mode of operation allows background reduction, smaller tracer doses, isotope identification, complex spectral distribution analysis and other related analyses.

With their inherent versatility of operation and application the RCLiacs are believed to be destined to become as universally accepted in the nuclear field as the oscilliscope is in the electronic field.

Readout

The RCLiacs have two basic readout modes, "Curve" and "Number". "Curve" readout plots graphically the total count recorded in each channel. "Number" readout displays the arithmetic total of counts received in each channel in decimal Arabic form. Both RCLiac models have switch-selected "Curve-Number" readout displayed on a cathode-ray tube which presents a photographic image for rapid and accurate recording of data for permanent reference.

Design

Reliability, precision and ease of operation have been designed into the RCLiacs. Design features which contribute to these parameters of operation are: 95% transistorization affording greater reliability and lower power requirements, printed circuitry throughout and modular construction affording unique adaptions for specific situations. Yet the RCLiacs are remarkably small in size and weight, actually portable.

Selection

Selection of your RCLiac should be based primarily on your facility's basic research requirements. For the modest laboratory the RCLiac-32 should be considered, while larger installations may require the RCLiac-128. The RCLiac-128 has four times the range of the RCLiac-32, affording a greater energy range in the spectrometry mode and a greater range of operation in the gross counting mode.

The finest spectrometry instrument now in use is the RCL 256-channel analyzer, the most widely accepted instrument for pulse-height analysis.

Your RCL representative can offer excellent counsel and help you in the proper selection of the right RCLiac for you. Write today for more detailed information on the RCLiacs and a list of representatives near you.

Introducing

RCLiac-32 and 128

transitorized multi-channel scaler-analyzer data processing systems

One instrument that performs all operations from detection to qualitative or quantitative analysis. All counting and analytical operations from simple gross counting through scintillation spectroscopy and pulse-height analysis can be accurately and rapidly processed by the RCLiacs. Representative features:

- Six plug-in modules
- Super-stable H.V. supply, continuously variable from 500 to 1500 volts
- Completely transistorized linear amplifier
- Preset time from 0.1 second to several days
- Preset count from 10 to several billion
- Maximum zero drift: ½ channel per day on RCLiac-32
  1 channel per day on RCLiac-128
- Maximum input pulse rate: 50,000 pps.
- Data stored in decimal form
- One million count capacity per channel
- Readout is "live" during accumulation in either "curve" or "number" mode
- Instant, permanent recording of data by use of Polaroid camera
- Outputs available for strip chart recorder and digital printer.

Atomfair Visitors

See the remarkable RCLiac-32 in operation at RCL's booth. Also see instruments representative of the complete line of nuclear instrumentation from RCL.

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NUCLEONIC PARK, SKOKIE, ILLINOIS

Radiation Counter Laboratories, Inc. Dept 138
Nucleonics Park, Skokie, Ill.

Gentlemen,

Please send me information on the ☐ RCLiac-32, ☐ RCLiac-128, ☐ RCL's 256 Channel Analyzer.

Name_____

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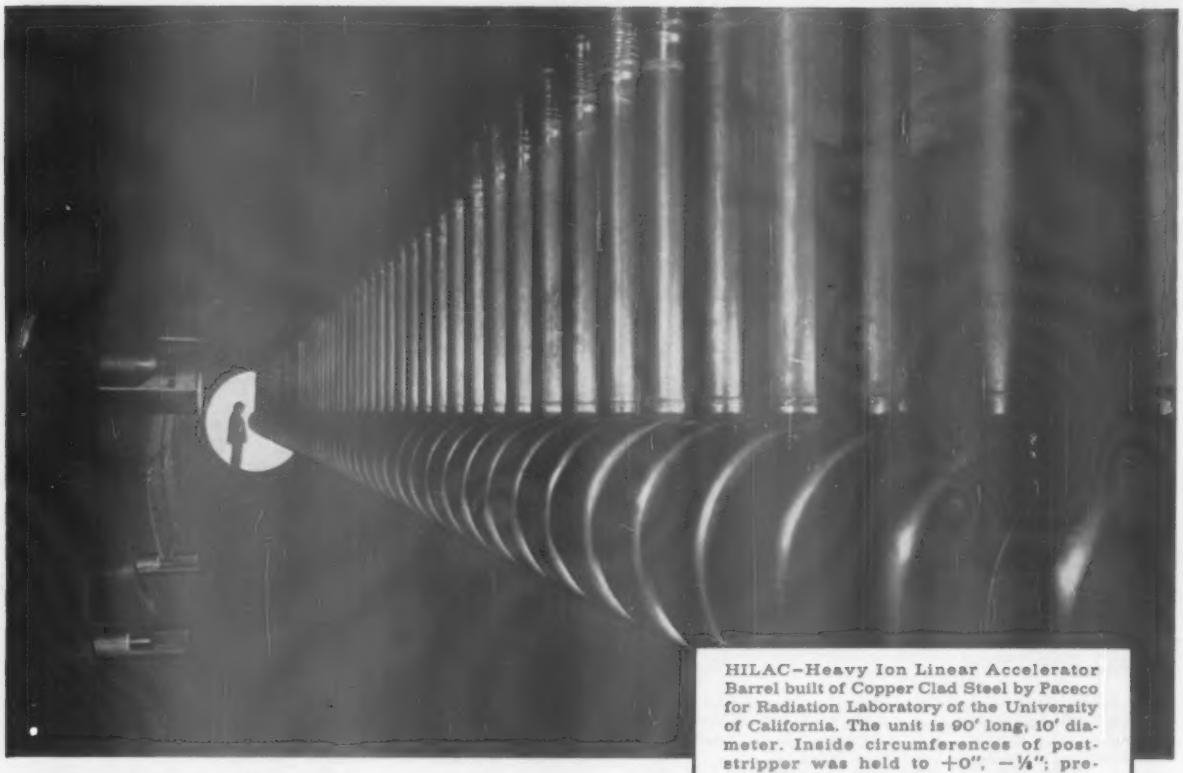

HILAC—Heavy Ion Linear Accelerator Barrel built of Copper Clad Steel by Paceco for Radiation Laboratory of the University of California. The unit is 90' long, 10' diameter. Inside circumferences of post-stripper was held to +0", −⅛"; pre-stripper +⅛", −0". In the manifold section tolerance of post-stripper was held to +0", −¼"; pre-stripper +¼", −0". Maximum out of roundness ±¼".

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- Exchangers for remote handling

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Formal Dedication of the Sodium Reactor Experiment Marks Significant Milestone in Nuclear Power Program

On November 14, 1957, in a building high in California's Santa Susana Mountains, a group of people witnessed a ceremony of great significance not only to America, but to mankind everywhere. What they saw was the official confirmation of the success of the sodium graphite type of nuclear reactor as a most promising new method of increasing resources of usable power in a power-hungry world.

They were watching the formal dedication of the Sodium Reactor Experiment, designed and built for the Atomic Energy Commission by Atomics International. The SRE includes an experimental atomic power reactor, which achieved sustained nuclear fission in April, 1957. In July reactor heat was used to generate electricity. The SRE has been performing as planned, supplying data on the practical aspects of designing and operating a power station based on the Sodium Graphite Reactor. The power produced by the SRE is being delivered for use to the homes and factories of the nearby San Fernando Valley. It was the first electricity ever to be supplied to the American public by a private utility from a non-military nuclear reactor.

NUCLEAR-POWERED SPARK
A switch is thrown at the dedication of the Sodium Reactor Experiment—and electricity from the atom surges into the lines of a private utility company.

THE ATOM GOES TO WORK IN SOUTHERN CALIFORNIA
In the rugged Santa Susana Mountains near Los Angeles, the Sodium Reactor Experiment is showing great promise as a practical source of electric power.

Basis for Large Power Stations

Atomics International designed the SRE to give a maximum output of about 6500 electrical kilowatts. This nuclear power plant is now in operation as part of the Atomic Energy Commission's program to develop efficient types of reactors to meet the growing worldwide need for power. Atomics International will use data from the SRE to design and construct large power stations like the 75,000 kilowatt plant planned for the Consumers Public Power District of Nebraska.

The Southern California Edison Company cooperated with Atomics International by providing a generating plant to turn the nuclear reactor heat energy into electricity and by distributing the power to its customers.

Other Achievements by AI

Another nuclear power approach being conducted by Atomics International for the Atomic Energy Commission is the Organic Moderated Reactor Experiment in Idaho, which has been operating since last September. This project will provide technical information for the construction of two 12,500 kw power stations—one in Piqua, Ohio; the other in a Latin American country. AI recently completed a study for the AEC's Maritime Reactors Branch which indicated that the OMR has technical and economic promise as a power plant for atomic supertankers and merchant ships.

Another power reactor concept, the Advanced Epithermal Thorium Reactor, is under study for the Southwest Atomic Energy Associates. AI research reactors are now operating in Japan, Germany, Denmark, and the United States. Others are being built for Italy and West Berlin.

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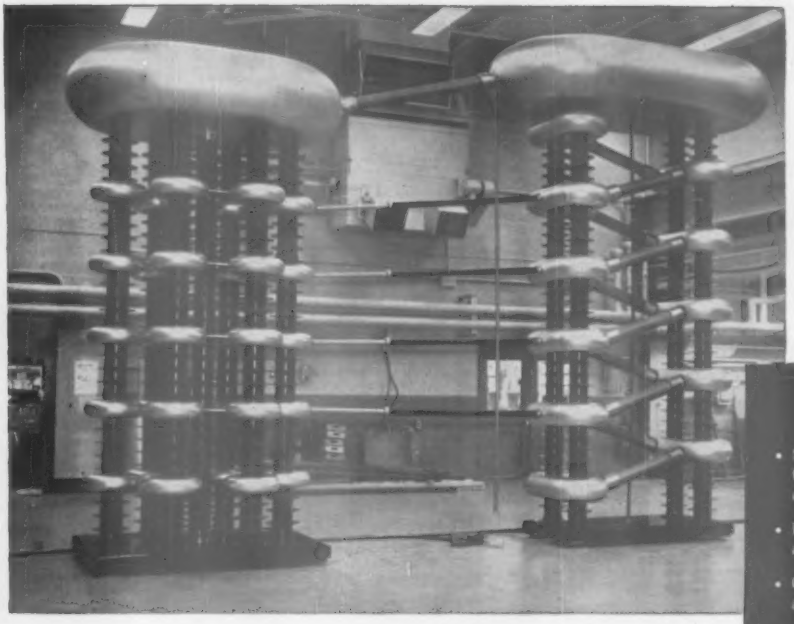

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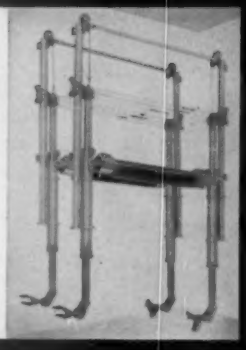
A general purpose manipulator for installation over a barrier wall or through a ceiling opening of a protective enclosure.



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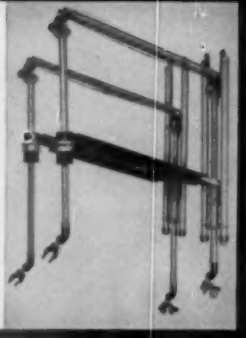
A space conserving, light weight manipulator for use in hoods or over thin walls where minimum clearances and easy portability are important factors.



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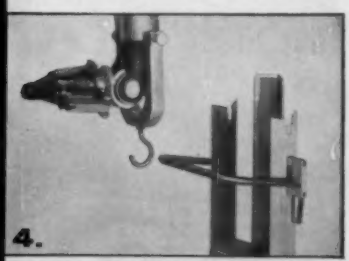

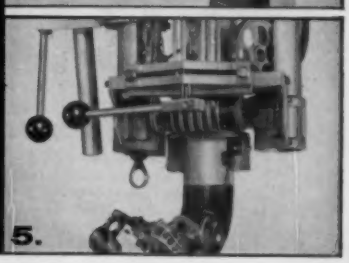

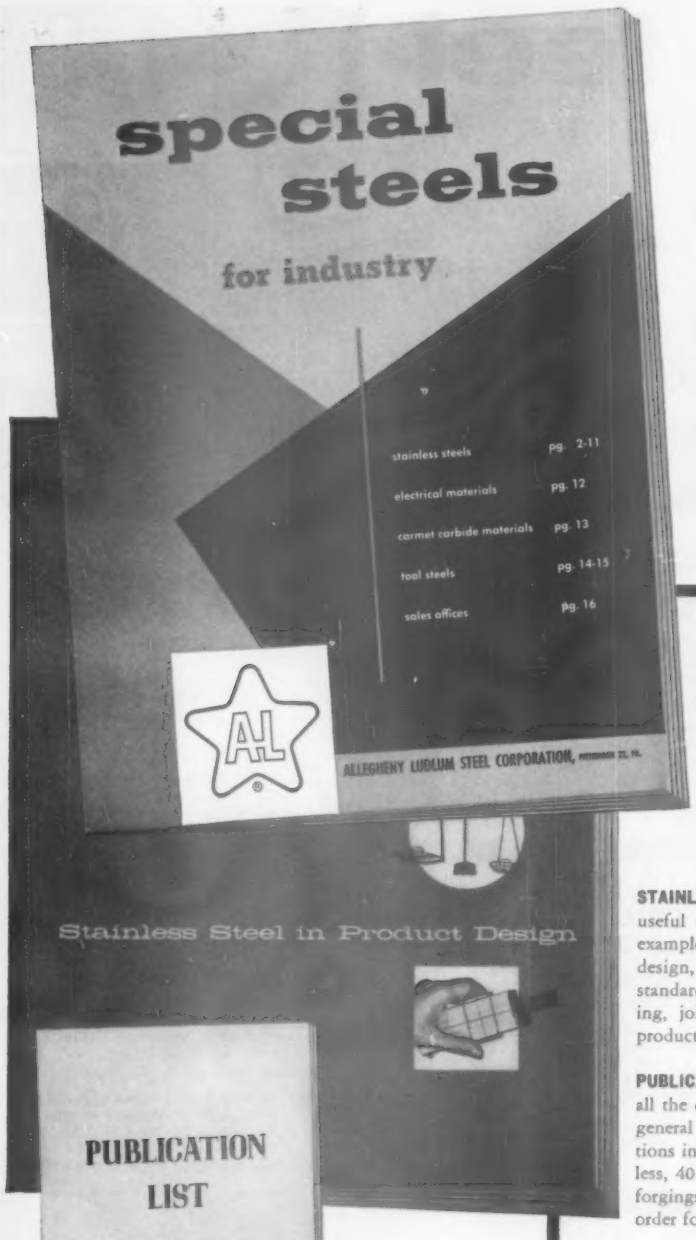

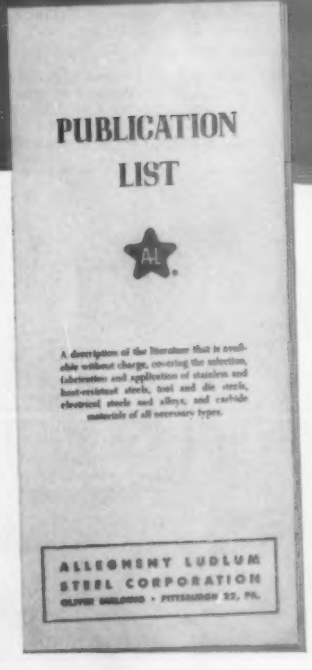

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STAINLESS STEEL IN PRODUCT DESIGN . . . 40 pages of useful engineering and fabricating data including practical examples showing where, when, how stainless steel improves design, adds benefits, helps sales. Information includes: standard sizes and shapes; designing for lower costs in forming, joining, finishing, etc. with many pictures of actual products made and designed in stainless steel.

PUBLICATION LIST . . . 8-page folder that lists and describes all the current publications offered by Allegheny Ludlum: 9 general publications, 14 on stainless, 10 on stainless applications in specific industries, 16 technical data sheets on stainless, 40 on tool steels, 20 on Carmet carbide materials, 5 on forgings and castings, 12 on electrical steels. There is a handy order form to use in getting the data you need.

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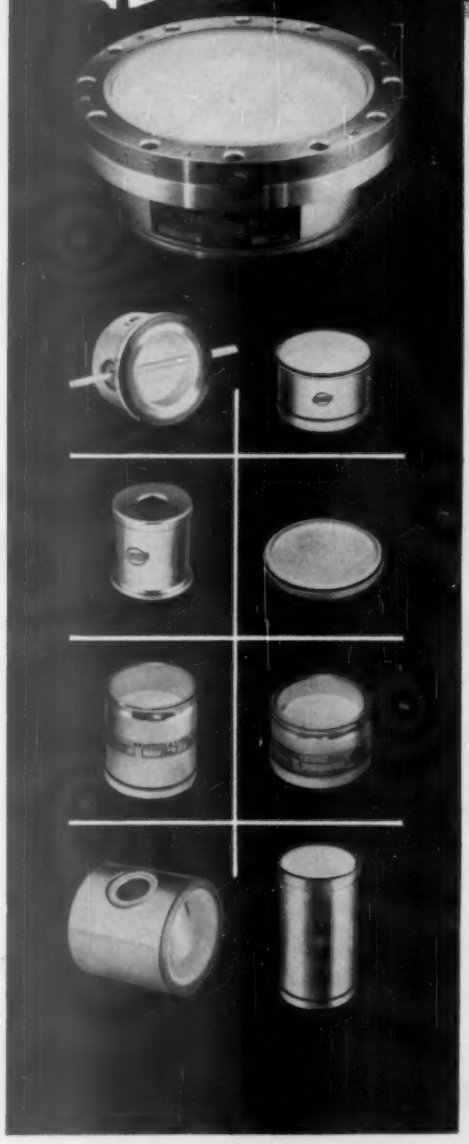

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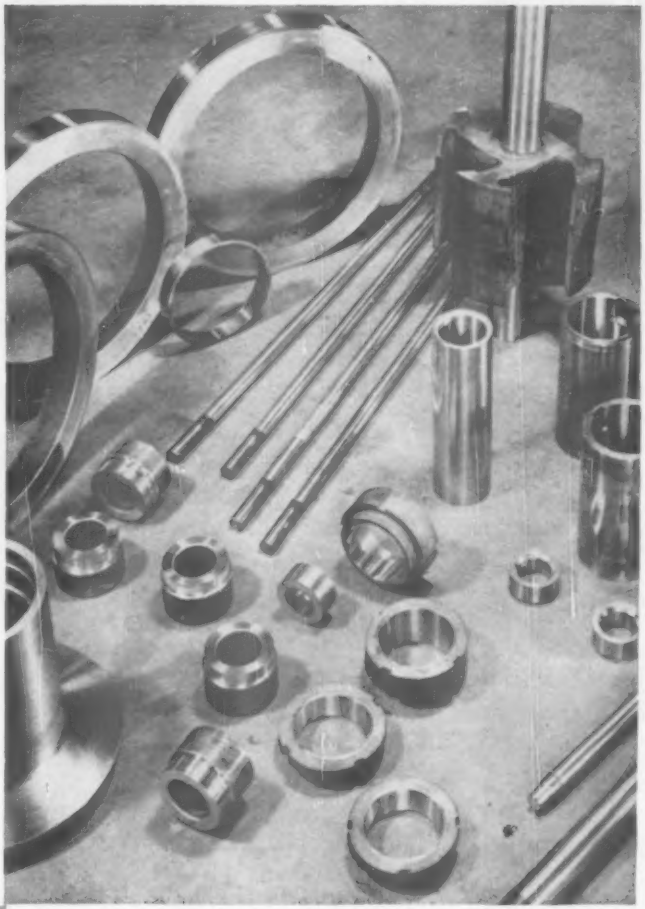

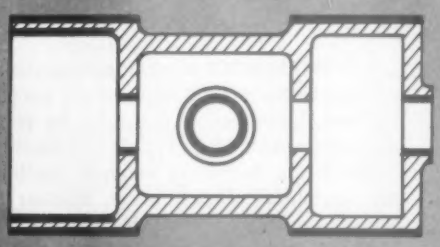

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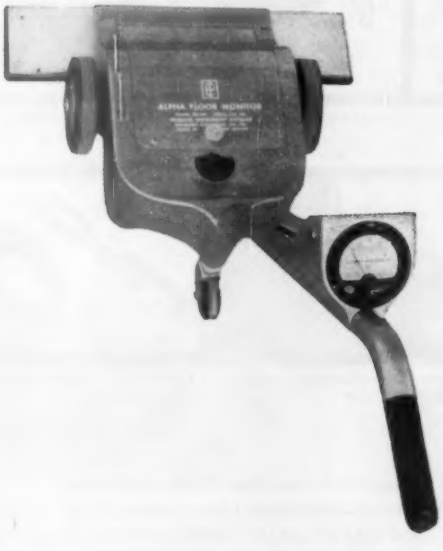

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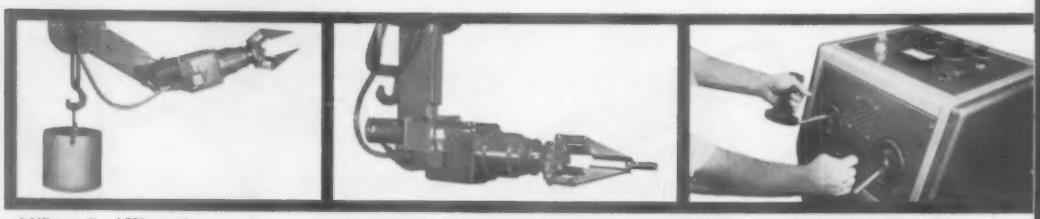

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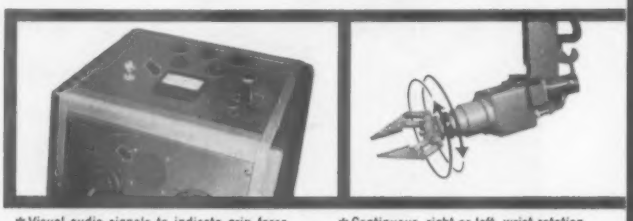
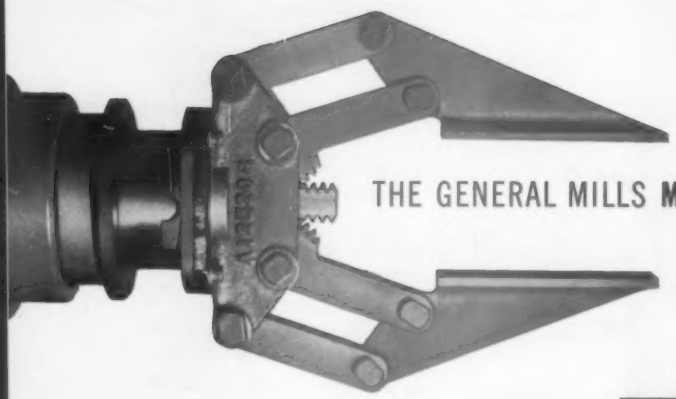


*Visual-audio signals to indicate grip force. *Continuous, right or left, wrist rotation.



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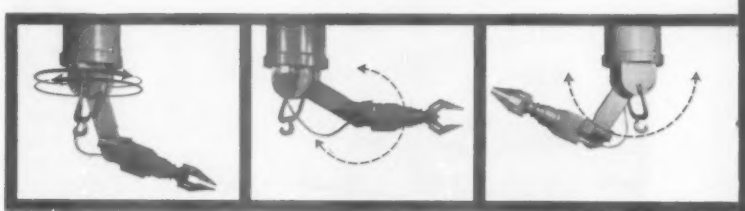

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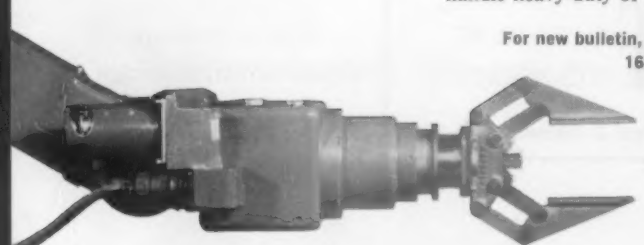

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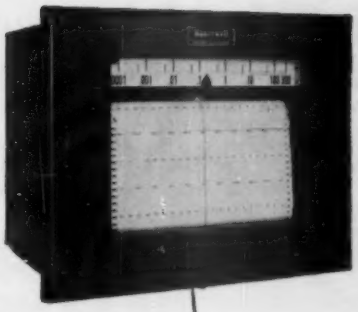

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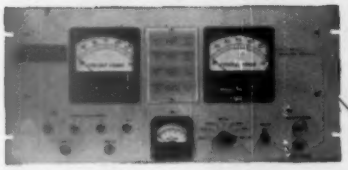

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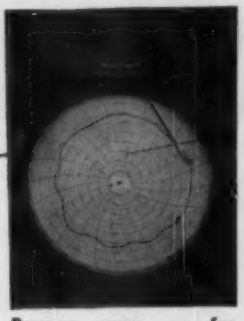

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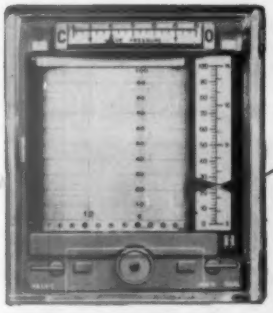

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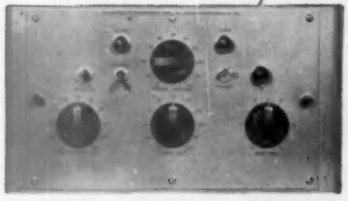

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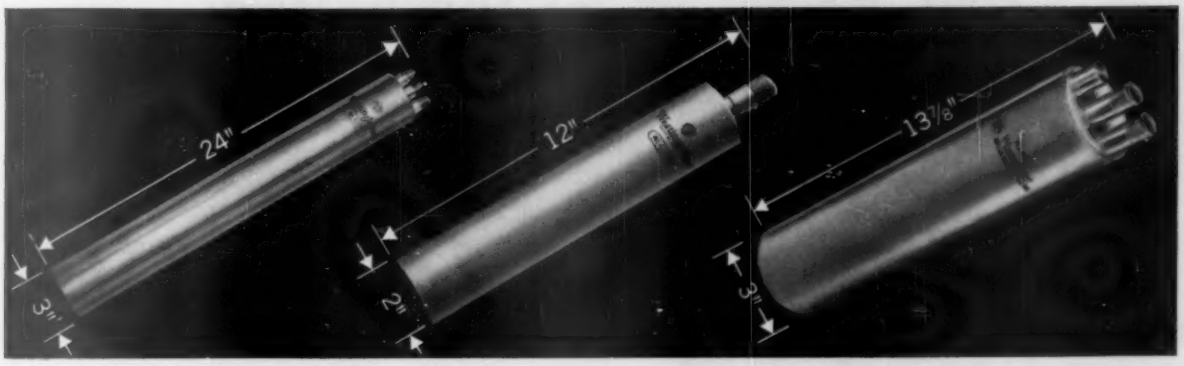

WL-6377 Compensated Ion Chamber:
Electrical compensation—guard ring design. All-magnesium construction—B^{10} coated electrodes. Thermal neutron sensitivity: 4.0×10^{-14} amps/nv. Gamma sensitivity: 3.0×10^{-11} amps/R/hour. Operating thermal neutron flux range: 2.5×10^{2} to 2.5×10^{10} nv. Passes Bu Ships 40T9 for vibration and MIL-S-901 for shock.

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WL-6937 Uncompensated Ion Chamber:
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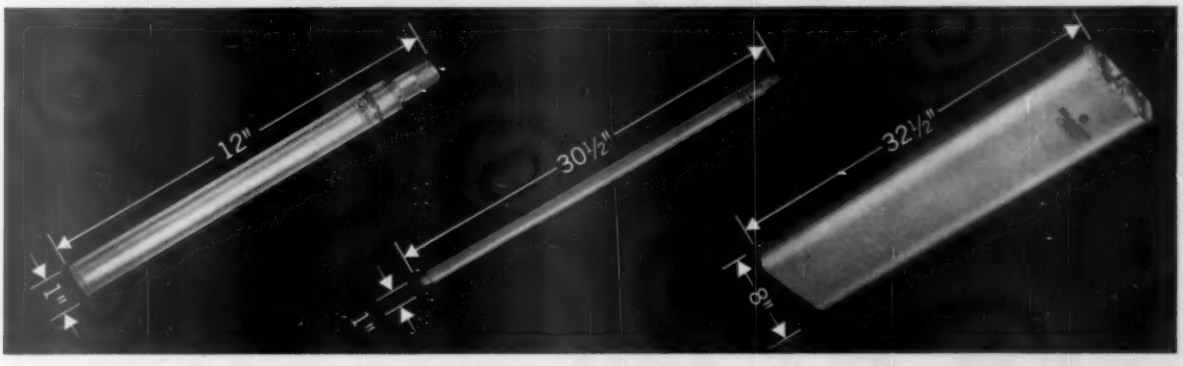

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Thermal neutron sensitivity:
4.5 counts /neutron/cm²
Operating range: 0.25 to 2.5×10^{4} nv
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WL-6998 BF_3 Proportional Counter:
All-aluminum body—enriched BF_3 filled
Thermal neutron sensitivity:
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Operating range: 8×10^{-2} to 8×10^{3} nv
Passes MIL-STD-167 (Type 1) for vibration

WL-6938 High Sensitivity Proportional Counter: Contains four elements similar to WL-6998 in polyethylene moderator. Aluminum body
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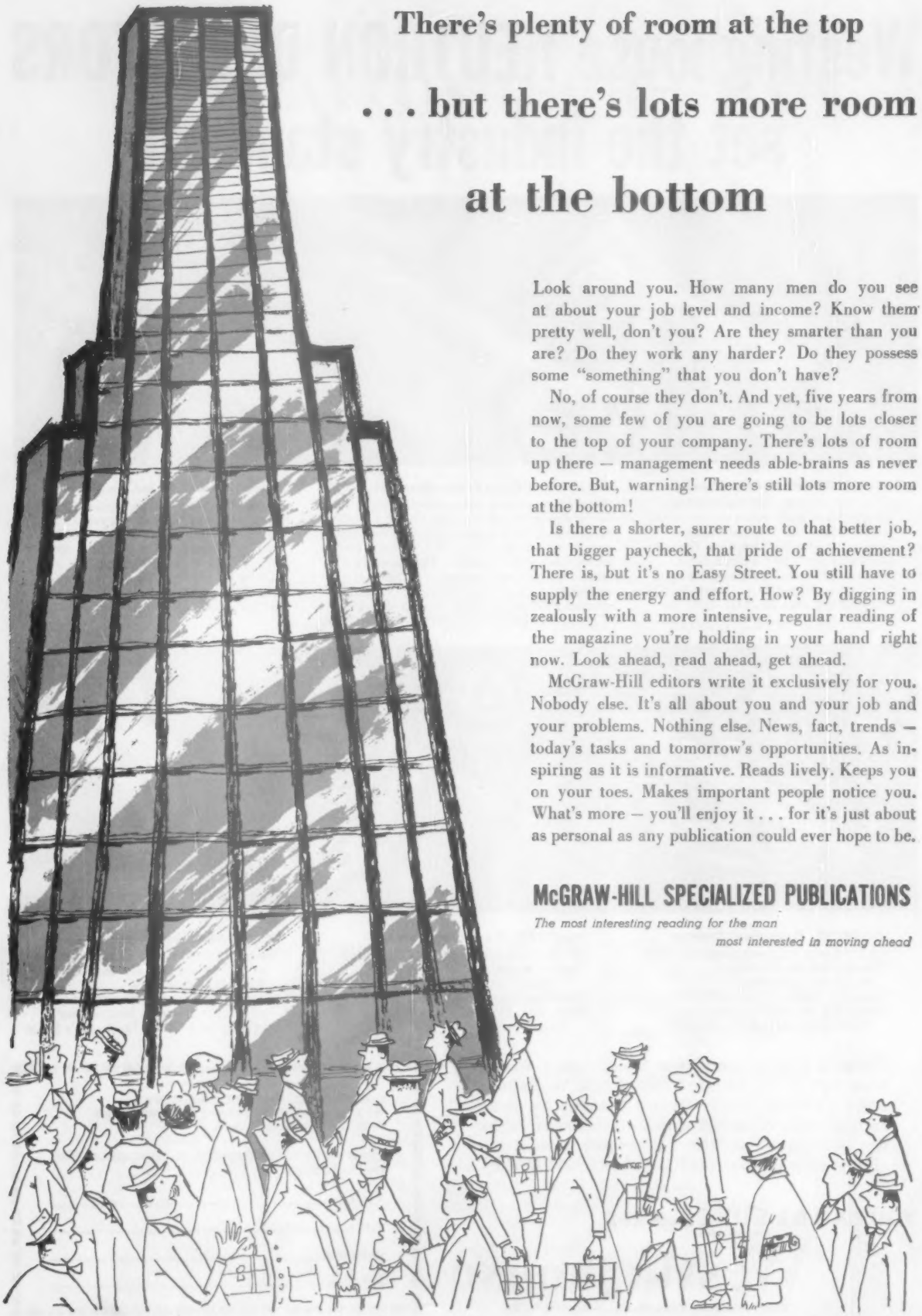

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ALITE DIVISION

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NUCLEAR VALVES

Complete separate facilities provide prime source of supply for expanding nuclear industry

With over 29 years of specialized experience as a leading producer of high alloy valves for the process and related industries, it was natural for Alloy Steel Products Co. to be called upon to help with the valve problems of the new and progressive nuclear industry. Alloy Steel Products Co. has contributed to the development and production of various types of valves for critical applications in nuclear reactor plants.

With the need for nuclear valves increasing so rapidly, Alloy Steel Products Co. recognized that the only right way to serve the nuclear industry was to set up a complete and separate Nuclear Division with extensive facilities for design, engineering, manufacturing, testing, and sale of the special types of valves required. Today, with a completely new plant, an engineering staff selected for technical background and experience in the nuclear field, and some of its nuclear valves actually in production, the Nuclear Division is an accomplished fact.

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- bellows sealed valves for highly radioactive, toxic or explosive fluids
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- high pressure "capped" valves for throttling, isolation, drain, and instrument lines
- manually operated gate and globe valves for a myriad of auxiliary high pressure and temperature services

The Nuclear Division of Alloy Steel Products Co. invites your inquiries on the above listed and other valves for nuclear application. The engineering services of the division are available to you for consultation on your nuclear valve problems. Write us at 1321 West Elizabeth Ave., Linden, N. J. B-4

FACTS ABOUT ALLOY STEEL PRODUCTS CO.

Although the reputation of Aloyco Valves is well known in the process industries, here are a few words about the Company for nuclear engineers.

Two facts make Alloy Steel Products' entry into the nuclear valve field a logical forward step. First, we have specialized for 29 years in one thing only—the design and manufacture of stainless steel and high alloy valves. We are the only company that does so. We built our own integrated foundry to produce a single product—pressure tight, mechanically sound stainless steel valve castings.

The same principle of putting quality first is evident in our design, engineering, machinery, control procedures and even our sales approach. Aloyco Sales Engineers handle one line only, know their business, and are equipped to be of real service to our customers.

This is a company that was built and has gone forward on the quality of its products. This is the second fact that makes our entry into the nuclear field, with its exacting requirements, so logical and inevitable. You can depend on the extremely high quality of Aloyco nuclear valves.

ALLOY STEEL PRODUCTS COMPANY

NUCLEAR DIVISION

Linden, New Jersey

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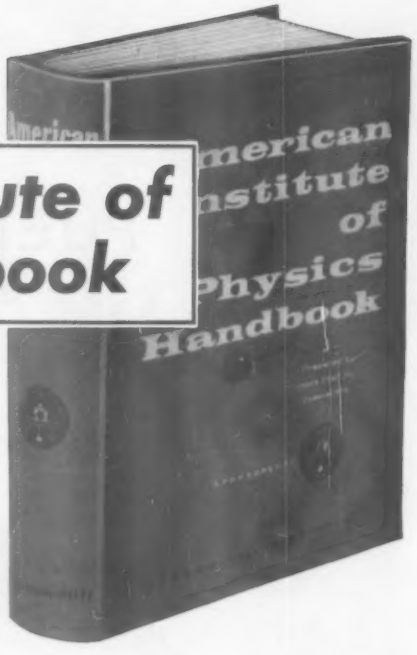

Dwight E. GRAY, Coordinating Editor

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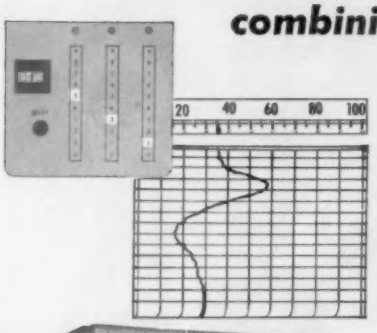

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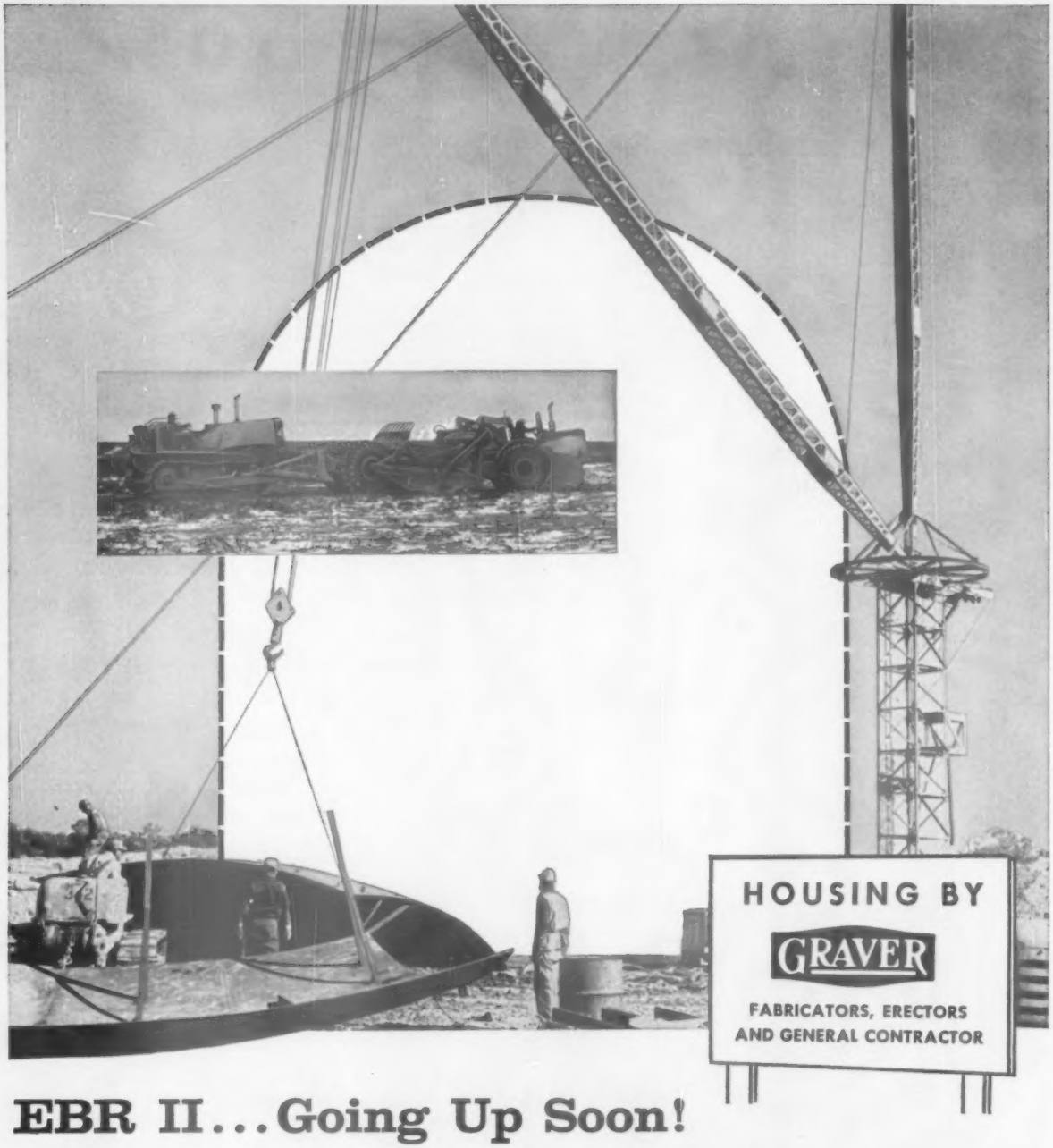

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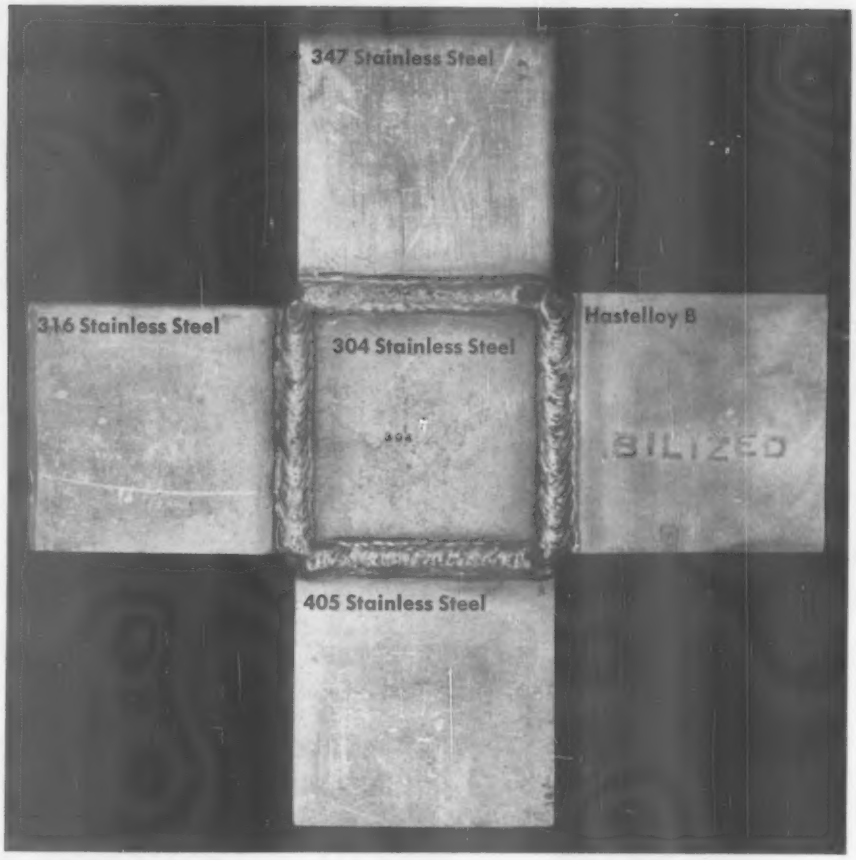

With versatile Inco-Rod "A", weldors produce strong, ductile joints in a wide variety of dissimilar alloys. In *this* test specimen, sound welds were produced between four different alloys and the Type 304 Stainless Steel plate at center.

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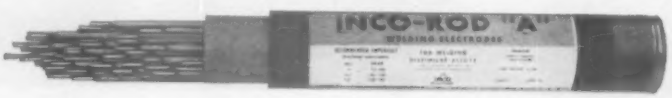


NUCLEONICS MARCH, 1958

Jerome D. Luntz, *Editor*

And Now, Outer Space

THE Atomic Energy Commission is supporting work in basic research, civilian nuclear power, nuclear ship propulsion, nuclear aircraft, nuclear rockets, thermonucleonics, etc. Now it has been proposed (see p. 20) that AEC be given responsibility for developing nuclear propulsion systems for outer space vehicles.

At the moment, nuclear engines are eminently worth investigating for interplanetary travel. They appear to offer the power, thrust and lifetime that competitive systems do not.

AEC is eminently suited to take on this new task. Through its contractors, it has the manpower and facilities available for the work. In addition, AEC has already proved it works well with the Armed Services in developing nuclear propulsion systems for military craft.

HAVING said this—and we want to make clear at this point that we *do* believe that work on outer space vehicles is important and that AEC should be given the job—we feel there is still one basic, nagging question that doesn't have an easy answer: How important is it for the U. S. to be strong, if not "first," in every phase of science and technology?

Recent events have embarrassed Americans into believing that unless they're first, ahead of the Soviet Union, they will suffer in prestige throughout the world. They believe that, as a consequence, they will lag in the "war for men's minds."

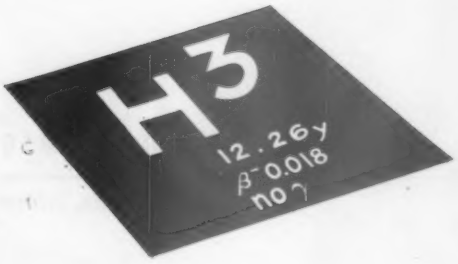
And so, in many fields that should not have been ignored previously but had been, they suddenly press ahead for the sake of being first. Sometimes when this is done the enterprise in question suffers from an immaturity of approach, from a lack of perspective.

Of course, in these days when military strength is of no small importance, activities having direct military implications must be pursued with vigor.

The need for this is not as obvious, however, in the many areas that don't have clear military interest. But today science and technology can easily produce unforeseen byproducts with greater significance than an originally intended goal. Thus, at the least, for military strength, but certainly for sound technological health, it is important for any vital country to maintain a vigorous scientific effort and to encourage the development of scientific talent.

BUT, in the realm of cementing our relationships with the free nations of the world and in developing our capabilities to assist such nations, there is little doubt that being "first" in the many contrived races that are before us is less important than many other "real" values: sincerity of purpose, strength of character, and basic solidity of our economy and our democratic processes.

These are the things that will pay off and are the values worth striving for.



Tritium Tracing —A Rediscovery

Better labeling techniques, more sensitive detection and lower price bring new usefulness to tritium. Good half-life and versatility make this radiohydrogen valuable to biologists, chemists and geologists

TRITIUM HAS recently been "rediscovered" as a tracer. Three developments have contributed:

(a) Tritium is cheaper. In recent years the price has dropped by a factor of 50—from $100 to $2 per curie.

(b) Detection is more efficient. In particular, liquid-scintillator counting techniques have made possible full-efficiency counting without self-absorption. This conquers the greatest technical difficulty—detection of the very weak (18 kev max) beta particles.

(c) Labeling is easier and more versatile. Recoil labeling that makes use of energetic tritons from the $Li^6(n,\alpha)T$ reactions in a nuclear reactor is effective for a wide variety of compounds, and discharge-tube labeling promises a means of using the same technique with simpler apparatus (*1, 2*). More recently a still simpler, still more versatile technique has been developed by K. E. Wilzbach at Argonne National Laboratory. This is gas-exposure labeling in which tritium serves as both a radiation source and the inserted label (*3*). Discharge-tube labeling and gas-exposure labeling have the impressive advantage that they can be carried out with simple apparatus.

There are other contributing causes for the tritium revolution. Tritium is a very useful tracer for biologists and organic chemists because it is the only radioactive form of hydrogen, the most common element in organics.

In spite of technical difficulties, tritium was used as a tracer before World War II. With the accelerated development of radioactivity techniques carbon-14 displaced it as the most used radiotracer for organics because of C^{14}'s easier detection and labeling. The current revolution is bringing tritium back into prominence and forcing scientists to reread prewar publications. Lower costs and wider use are making it possible to exploit many of its advantages: useful half-life, high specific activities, low cost, etc. Even the weakness of its betas is sometimes an advantage, particularly in producing high-resolution radioautographs (see box p. 64).

Ten experts in the use of tritium offered a detailed picture of the state of the science at a recent symposium sponsored by the New England Nuclear Corp., Atomic Associates, and Packard Instrument Co. They spoke on labeling techniques, detection, health-physics considerations, and uses in the pharmaceutical industry, petroleum-reservoir engineering, biochemistry, and radioautography.

TRITIUM LABELING

Tritium's usefulness as a tracer has been greatly increased by the gas-exposure labeling technique developed by K. E. Wilzbach and described by him at the symposium. The compound to be labeled is exposed to tritium gas, which serves a double function: beta particles activate either gaseous tritium or the molecules of the compound, and this promotes exchange between hydrogen in the molecule and gaseous tritium. (It is not clear whether the mechanism is activation of tritium or activation of the exposed molecule, but the difference is not important to people who want to use it.)

Other tritium labeling methods are the tritium-recoil method (*1*) and chemical synthesis and exchange techniques, which can be used in combination with gas exposure and recoil. Gas exposure has the advantages of smaller radiation damage and simpler laboratory techniques.

In both gas-exposure and recoil labeling the product usually contains small amounts of high labeled impurities. Removal of these by-products requires efficient purification procedures. These lead to most of the effort involved in using the two methods.

Gas-Exposure Procedure

Good gas-exposure labeling requires isotopic purity, relatively high tritium pressures (~1 atm) and large surface area in the exposed sample. Wilzbach uses tritium of about 90% isotopic purity. The presence of He^3, formed by tritium decay, has no apparent effect on the process, but accumulation of hydrogen and methane makes it unwise to reuse the gas. Higher pressures increase both the activation and the tritium available for exchange; however, present techniques limit pressures to just below atmospheric (Fig. 1).

For safety and economy it is advantageous to use a limited amount of gas and a small sample. Subsequent dilution is better than using a large sample to start with. Since the tritium beta has a range of only 0.7 mg/cm², it is best to use solids in finely powdered form and to shake liquids. Room temperature is generally satisfactory, but some compounds display better labeling at reduced temperatures.

Apparatus. Figure 1 shows a typical reaction vessel and the pumping system used to introduce tritium. Samples consisting of 0.1–1 gm of liquid or powdered organics are introduced into the 6-ml vessel through the constriction, which is subsequently sealed off. Volatile samples can be introduced into a similar vessel from the Toepler pump.

After the vessel has been filled with sample and placed on the pumping apparatus, ~2 cm³ (5 curies) of tritium are introduced from a storage bulb or by distillation from uranium tritide. The vessel is then pulled off at the capillary. Shaking promotes the reaction with liquid samples, and with solids it is customary to rotate the tube and distribute the sample as well as possible over the walls.

The length of the gas exposure depends on the extent of radiation damage. This is expressed in terms of G_{-M}, the number of molecules destroyed per 100 ev absorbed. Unfortunately this number has been measured for only a limited number of organic compounds, but the available values have been tabulated (*4*). Its value determines the length of the optimal exposure. G_{-M} ranges between 1 and 10, and optimal exposures are usually 10–30 curie-days per millimole.

Incorporation of tritium is expressed in terms of G_T, the number of tritium

Gas-Exposure Labeling—Apparatus and Results

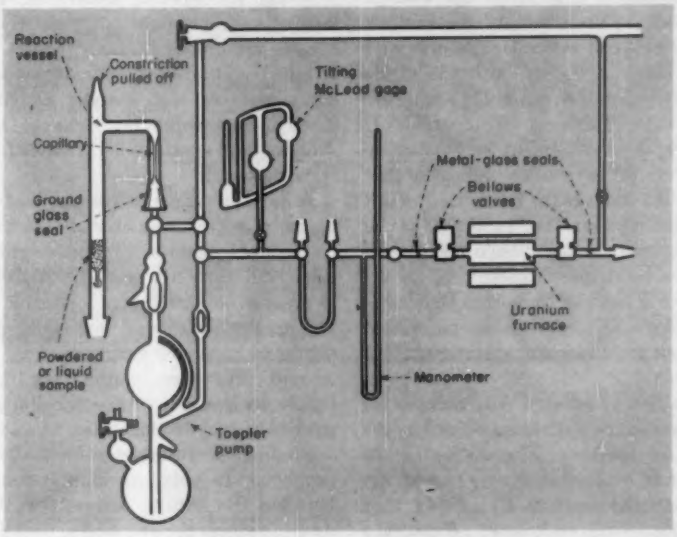


FIG. 1. System above permits introduction of gaseous tritium and powdered or liquid samples into vessel at upper left. Tritium comes from storage bulb mounted on U-tube or by distillation from uranium tritide

TABLE 1—Tritium Labeling by Gas Exposure

Compound exposed	*Sample weight (gm)*	*Exposure (days)*	*Amount of tritium (curies)*	*Tritium incorporated*			*Values of G_T*	
				Total (mc)	*Labile (mc)*	*In pure product (mc/gm)*	*Crude*	*"Pure"*
Toluene	0.86	2.9	7.5	42.7	None	22.2	0.22	0.10
n-Heptane	1.37	9.8	6.9	17.5	None	1.3	0.27	0.003
Benzoic acid	1.31	5.0	6.4	156	40	14.0	0.57	0.067
Sucrose	4.0	6.7	14.0	593	480	5.0	0.72	0.024
Cholesterol	1.88	4.8	7.2	335	90	64.3	1.11	0.40
Digitoxin	0.50	5.8	7.5	438	182	90	1.16	0.13

TABLE 2—Distribution of Tritium in Toluene

The specific activities of these toluene derivatives . . .		. . . indicate this tritium distribution in gas-exposure-labeled toluene
Compound	*Specific activity (μc/mmol)*	*Per cent of tritium at various positions*
Toluene	18.9	8.5 CH_3; 27.2; 27.2; 12.2*; 12.2*; 12.7
Pentabromotoluene	1.6	
Benzoic acid	17.3	
p-Nitrobenzoic acid	14.9	
2,4-Dinitrotoluene	11.0	
2,4,6-Trinitrotoluene	6.2	

* By difference.

atoms incorporated per 100 ev absorbed. For purposes of computation it is assumed that all of the tritium radiation is absorbed by the sample. The results of several exposures and the values of G_T for both the crude mixture and the purified parent are shown in Table 1. Comparable G values for recoil labeling are smaller by a factor of 10^5, which indicates that radiation damage for the same amount of labeling can be expected to be considerably smaller when the gas-exposure technique is used. As an example, it has been reported that ribonuclease and lysozyme can be labeled without great loss of enzymatic activity (*5*).

Position of label. Wilzbach has investigated the positions assumed by the label in toluene. The method is to separate derivative fractions and determine the amount of activity that remains with each one. From the data one can determine the fraction of the total toluene activity that is associated with each of the hydrogen positions in the toluene molecule. The results of these investigations are shown in Table 2.

Conventional Labeling

When the special nature of the labeled molecule does not require the special techniques of gas exposure or tritium recoil, simpler methods produce compounds of high specific activity. These include reduction, exchange, hydrolysis, and synthesis by means of intermediates.

Reduction. This is the method of choice if a precursor is available that has a double bond or a reducible group such as a carbonyl radical. Activity as great as 58 c/millimole is possible by this method, although one could not expect to keep such a compound under control. However, curies per millimole are possible even after dilution with carrier hydrogen.

Finding a suitable solvent is a problem. In polar solvents exchange between the tritium and solvent hydrogen reduces the eventual activity by a large factor. Modification of the compound before the reduction and subsequent restoration to the desired form often simplifies the problem.

Simple exchange. This method is limited by the fact that labels that go in easily come out easily; if a tracer is easily prepared, it is likely to be unstable, and vice versa. The method is useful if the exchange-labeled molecule is quickly modified to a stable form after the initial labeling.

Catalyzed reactions. Acid-catalyzed reactions are useful for aromatic compounds. The usefulness is limited by the tendency toward sulfonation. Other types of molecules, notably acetone and fatty acids, can be labeled by base- and metal-catalyzed reactions, respectively.

Hydrolysis. The following equations illustrate labeling by hydrolysis. As applied to benzene derivatives this method has the advantage of providing specific labeling. Reactions with the Grignard reagent, illustrated by the first two equations, have rather general applicability.

$$RMgX + H_2^3O \rightarrow RH^3 + H^3OMgX$$

$$SOCl_2 + H_2^3O \rightarrow SO_2 + 2H^3Cl$$

$$H^3Cl + RMgX \rightarrow RH^3 + MgXCl$$

$$CaC_2 + 2H_2^3O \rightarrow H^3C{\equiv}CH^3 + Ca(OH^3)_2$$

$$KCN + 2H_2^3O \rightarrow H^3COOK + NH_3^3$$

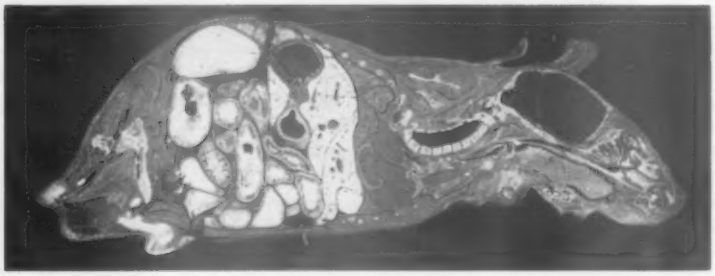
$$Cl_3CCHO + NaOH^3 \rightarrow Cl_3CH^3 + HCOONa$$

TRITIUM DETECTION

The current "rediscovery" of tritium as a tracer arises in part from development of new sensitive methods for detecting it. The beta particles have a maximum energy of only 18 kev, which means that few of them will penetrate even the thinnest window. Even more important, almost any tritium sample, no matter how thin, will absorb most of its own beta energy.

Two counting techniques conquer the difficulty effectively—liquid scintillation and gas counting.

The more powerful of the two is liquid scintillation counting, which has been widely developed in the past few years (*6–12*). The sample is dissolved or suspended in the scintillating liquid or gel. Thus there is a minimum of self-absorption and essentially no barrier between sample and detector. Beta energy is converted immediately into light, and the light can transverse the scintillating substance without the absorption experienced by beta rays. Such a system will recognize as little as 25 $\mu\mu c$ of tritium. In a recent extension of the liquid-scintillator technique, leaf patterns have been squeezed



Tritium Radioautography

Spectacular print* shows distribution of tetracycline in a mouse sacrificed 20 min after intravenous injection. Concentration is high where this figure is light. Brain at right shows low, while kidney at upper left shows high concentration. This exposure required 2.5 months.

Short range of tritium betas produces resolution that is unusually high for radioautographs. In microscopic enlargements individual cells are frequently distinguishable.

At the tritium symposium Walter L. Hughes gave figures to indicate the specific activity required in thymadine to label a mammalian cell: one locus requires 5 silver grains, which, at 5% efficiency, require 100 disintegrations, which might occur during a 1-month exposure. This is $\sim 10^{-9}$ curies per locus. Taking into account the composition of the average cell, one finds that one needs 0.2 curies per mole of thymadine.

* Torsten André, *Farmakologiska Avdelningen, Kungl. Veterinärhögskolan* (1956); published as supplementum 142 to *Acta Radiologica*.

Tritium or Carbon-14?

Since most organics are made up of hydrogen, carbon, and oxygen, and since there is no usable radioactive oxygen, organic tracers must be tagged with tritium or C^{14}. Both are weak beta emitters so the same instrumentation for detection and assay is applicable to both.

F. Marott Sinex, chairman of the recent symposium, made a comparison of tritium and C^{14} for tracer purposes. Here are some of his figures:

Carbon-14		Tritium
Maximum beta energies		
0.158	Mev	0.018
Dose from 1 mc uniformly distributed in a 70-kg man:		
0.039	rep/day	0.0044
Cost of the isotope. C^{14} is sold at Oak Ridge in solid $BaCO_3$ at specific activities up to 80 mc/gm. Tritium is sold as the pure gas except for the He^3 decay product.		
28	$/mc	0.002
Cost of labeled compounds. For example, here are the price of tritium-labeled leucine and C^{14}-labeled amino acids:		
800	$/mc	35
Specific activities. Tritium's much shorter half-life (12.3 yr compared with 5,600 yr) indicates that it takes much fewer atoms to make a millicurie than is the case for C^{14}. Thus maximal specific activities for the two are		
5	curies/mole	700

into filter paper that contains the scintillator (*13*).

In the other method one introduces tritium-labeled gases including tritium gas itself into gas counters to reduce absorption. This leads to two types of counting: conventional G-M counting with the tritium in the counter initiating the discharges and gaseous scintillation counting (*14, 15*). (See Table 3, page 67.)

Liquid Counting

Today's techniques for liquid-scintillation counting require a solution that has five components aside from the sample that is to be counted. This solution is viewed by two photomultipliers operated in coincidence to reduce background. Further background reduction is accomplished with pulse-height discrimination.

Scintillating solutions. The five components of a good scintillating solution are (a) an aromatic solvent, (b) a fluorescent dye, (c) a wavelength shifter, (d) a diluent in which the sample can be dissolved, and (e) naphthalene as a light restorer.

Solvents that are frequently used to hold the dye are toluene, xylene, triethylbenzene, ethylhexene, etc. Preferably one uses a solvent that will not attack Lucite, since Lucite is the most convenient container because of its high transparency. Terphenyl and diphenyloxazole (PPO) are the most useful dyes.

The purpose of the wavelength shifter is to absorb the light emitted by the dye at 3,500–4,000 angstroms and re-emit it at wavelengths closer to the phototube peak of ~4,600 angstroms. Most commonly used is POPOP, standing for phenyl-oxyzol-phenyl-oxyzol-phenyl.

Samples that do not dissolve readily in the basic three-component mixture can be introduced after introduction of an appropriate diluent. Water can be introduced at the cost of increased light absorption, and quartenary amine bases make it possible to dissolve carbon dioxide and proteins. Some of the light lost upon introduction of diluents is restored to the detection system when napthalene is added.

Electronics. Even when most of the energy of a tritium beta is efficiently converted into light in a scintillator it still produces a relatively weak pulse at the output of a photomultiplier. A counting system that is sensitive enough to detect these pulses is sensitive to many background pulses. The two devices that are used to reduce background are coincidence counting of two phototubes looking at the same scintillator and pulse-height discrimination. Coincidence counting eliminates essentially all of the thermal-noise pulses, which have energies comparable to those that originate from tritium scintillations. Discrimination against high-energy pulses eliminates most of the pulses that originate from non-tritium radiation absorbed in the scintillator. Two-channel pulse height counting makes possible simultaneous counting of the two most useful organic tracer nuclides, tritium and C^{14}. An upper channel counts only C^{14}, and a lower one counts tritium and some C^{14} pulses as well.

Improvements in liquid-counting equipment are reducing technical difficulties. Figure 2 shows one example, an automatic sample changer that enables long counting runs without any exposure of sensitive elements to light. This saves time since extensive dark adaption is required for low-noise counting.

Other Assay Techniques

Most non-scintillation methods for tritium assay depend on conversion of the labeled compound into a suitable gas. Methods that have been found useful for conversion and assay are described by Fig. 3 and Table 3, and the bibliography (p. 67). Charles V. Robinson described these methods at the symposium and prepared the figure, table, and bibliography.

FIG. 2. Automatic sample changer for liquid scintillation counting permits long runs without interruption by exposure to external light

Radioautography. Photographic detection is also used with tritium betas, principally in making radioautographs. An example is the figure shown in the box on page 64. The low energy of the particles is at once an advantage and a disadvantage. The short range in emulsions leads to extremely fine resolution. On the other hand, exposures of several months are

frequently required to produce recognizable darkening.

APPLICATIONS

The usefulness of tritium as a tracer comes from the presence of hydrogen in most organic substances and the existence of tritium and tritium-labled compounds as gases. Four of the symposium speakers discussed practical tracer uses of tritium.

Biology and Drugs

The manufacturer of pharmaceuticals uses tracers primarily to study new drugs. The things he wants to know about them are (a) chemical and biological stability, (b) site and extent of absorption, (c) translocation and distribution in body fluids and organs as functions of time, (d) biological half-life, (e) places of permanent or semi-permanent storage, (f) biological transformations and methods of excretion and (e) modes of biochemical and pharmacological action.

Tritium labeling by exchange methods is possible with most drugs. Testing is performed largely in animal experiments, and assay is by liquid-scintillator counting and radioautographs.

In new-drug studies, tests to find an appropriate labeling technique and then to test the quality of the label are always fundamental. A label can arrive at a spot through movement of the whole molecule, transfer of part of the molecule in a metabolic process or merely by exchange of the tritium atom with the hydrogen of another molecule.

One must also evaluate isotopic effects. Tritium can move preferentially in chemical or biological systems as the result of two things: (a) the different strengths of hydrogen and tritium bonds and (b) the different mobilities exhibited by atoms containing hydrogen and their counterparts containing tritium.

Petroleum Engineering

Oil geologists find tritium useful in studying fluid flow in both laboratory experiments and underground exploration. Tritium has several advantages over other tracers: (a) a cost that is a small fraction of the total cost of a test, (b) weak radiation that presents no health hazard, (c) relatively long life, (d) detection techniques that can be used in the field, (e) absence of appreciable tritium in naturally occurring gases and (f) the ability to incorporate it as a label in the fluid that is to be traced, which is usually water or a hydrocarbon.

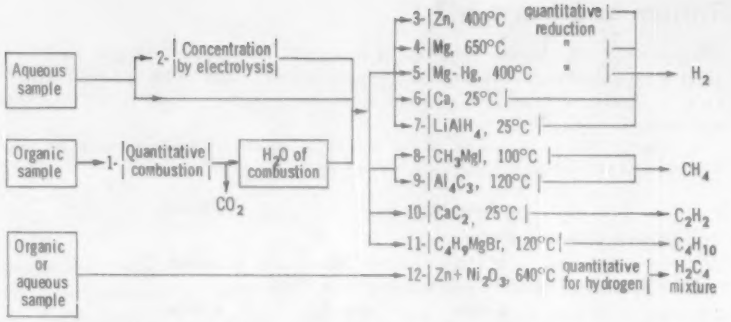


FIG. 3. Conversion methods for gas counting of tritium. Table and references on the next page list users, methods, and publications. Numbers associated with conversions above appear in fifth column of the table. References should not be confused with story bibliography on this page

In a "five-spot" technique oil is taken from a central producing well while four other wells are used as injection wells. Water or gas forced down an injection well will force oil to the site of the production well. Different tracers, used together, indicate which of the injection wells are effective. Tritium-labeled gases that are useful are tritium itself, CH_4^3 and $C_2H_6^3$. Other radioactive gases that are frequently used are $C^{14}H_4$, $C_2^{14}H_6$ and Kr^{85}. Dilution factors as great as 10^{13} are currently usable.

Many nonradioactive gas tracers have been used in the past. They include dyes, boron compounds, ammonia, salts, helium and carbon monoxide. However, such tracers present many difficulties: (a) failure to behave as the fluid to be traced, (b) lack of sensitivity, (c) high cost and (d) need for laboratory techniques that cannot be used in the field. In the use of helium there is inconvenient background due to naturally occurring helium. Carbon monoxide presents a special health hazard.

If the flooding fluid is water, tritium-labeled water is the ideal tracer. Other long-lived tracers are usable if they are chemically complex so that they do not react with the materials they encounter.

Another special problem is the labeling of gases held in underground storage reservoirs. The technique is appropriate for measuring the size of the reservoir and finding leaks that can waste the stored gas or poison nearby mines. Currently reservoirs are tagged at levels that permit tracing their gas for 25–30 yr. This requires about 1 c per million cubic feet.

Cost of homogeneous labeling is $2–3 per million cubic feet. The cost per injection includes similar costs of a few hundred dollars for isotope procurement and calibration, respectively, and an injection cost of a few thousand dollars.

* * *

This article is based on material presented at the Symposium on Tritium in Tracer Applications, Hotel Statler, New York, November 22, 1957.

The speakers were F. Marott Sinex, chairman, Boston University School of Medicine, Kenneth E. Wilzbach, Argonne National Laboratory, Seymour Rothchild, New England Nuclear Corp., James R. Arnold, Princeton University, Charles V. Robinson, New England Medical Center, John S. Handloser, Brookhaven National Laboratory, Jay F. Snell, Pfizer Therapeutic Institute, Donald R. Carr, Isotopes, Inc., Maxwell Eidinoff, Sloan Kettering Institute, Walter L. Hughes, Brookhaven National Laboratory.

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TABLE 3—Gas-Assay Methods for Tritium

Principal author	*Refs. listed below†*	*Type of sample*	*Size of sample (approx.)*	*Conversions (Fig. 3)*	*Labeled gas product*	*Fraction of activity in sensitive volume*	*Gases added*	*Mode of operation**	*Remarks*
Eidinoff	4	organic	10 mg	1, 3	H_2	0.5	A, C_2H_5OH	G-M	see also Verly
Jones	5	H_2 gas	1 mm	none	H_2	most	A, C_2H_5OH	G-M	used for absolute count
Libby	6–8	H_2O	1 liter	2, 3	H_2	0.3	A, C_2H_4	G-M	used for low specific activities
Henriques	10	H_2O	220 mg	5	H_2	most	none	Lauritsen electroscope	see also ref 11 which uses same conversion
Bernstein	12	H_2 gas	various	none	H_2	most	none	prop.	
Hawkings	13	H_2O	various	3	H_2	most	CH_4	prop.	used for absolute count
Verly	14	organic	10 mg	1, 3	H_2	0.5	CH_4	prop.	see also Eidinoff
Eutsler	15	H_2O	1 ml	6	H_2	0.1	none	ion ch.	portable monitoring
Healy	16	H_2O or urine	1 ml	6	H_2	0.1	none	G-M	uses quenching circuit—relatively fast assay
Biggs	17	organic	to produce 150 mg H_2O	1, 7	H_2	0.3	none	ion ch. vib. reed	
Robinson	18–19	H_2O	200 mg	8	CH_4	0.1	none	prop.	gas moved by partial trapping
White	20–22	H_2O	300 mg	9	CH_4	0.25	none	prop.	
Wing	23	H_2O	100 mg	10	C_2H_2	0.1	A	G-M	relatively fast assay
Glascock	1, 24, 25	H_2O	10 mg	11	C_4H_{10}	0.25	C_4H_{10}	G-M	gas is moved quantitatively by cold traps
Wilzbach	26, 27	organic or H_2O	5–10 mg	12	mixture H_2, CH_4	most	CH_4	ion ch. vib. reed	one step conversion of organic sample
Christman	28	organic or H_2O	5–10 mg	12	mixture H_2, CH_4	most	A, CH_4	prop.	one step conversion of organic sample

* prop. = proportional counter; ion ch. = ionization chamber; vib. reed = vibrating reed electrometer.

† **GAS-ASSAY BIBLIOGRAPHY—REFERENCES FOR FIG. 3 AND TABLE 3**

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Fast-Breeder Power Reactors: Where Does U. S. Program Stand?

Progress in fast-breeder hardware includes development of radiation and temperature-resistant fuel element alloys and successful tests of full-scale, high-temperature Na components

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DEVELOPMENT OF FAST-REACTOR TECHNOLOGY in the U. S. is following a broad pattern involving development of fuel materials and designs, reactor systems (Table 1) and components and fuel processing and fabrication. In addition to this general development program, three fast-reactor projects—Experimental Breeder Reactor-II, Los Alamos Molten Plutonium Reactor Experiment-I and the Enrico Fermi Fast Breeder Reactor (see table of fast reactors)—are under construction.

Still unanswered is the question: When will fast reactors achieve the status of U. S. power reactors on-the-line? The answer depends partly on technological factors but mostly on economics—if fast power breeders are to compare favorably with thermal reactors, they must offset their costlier construction and operation by a higher breeding ratio.

The object of this discussion is to outline present activities in the U. S. program (see Figs. 1 and 2) and to suggest areas requiring most attention in future developmental work. The discussion will cover the general areas mentioned in the first paragraph and the three reactor projects.

Fuels and Fuel Elements

All three fast reactors under construction in the U. S. are sodium-cooled and operate at moderately high temperatures to permit efficient energy conversion. EBR-II and the EFFBR will generate electrical power and will employ "full-scale" sodium-system components, which will require little extrapolation for application in larger plants.

Fuel loadings for the three reactor-construction projects have been selected. Work presently in progress is directed toward improving fabrication processes and operational characteristics of the fuels.

Solid-metal fuel. EBR-II and EFFBR will use pin-type fuel elements. Both reactors are designed to operate at maximum fuel temperatures of about 1,300° F at full power. Although actual reactor operating experience is not available at these fuel temperatures, there is evidence that it will be permissible.

The EBR-II fuel-element development program is unusual in that it will use a rather complex alloy established by the melt-refining purification process. This process does not remove all the fission products resulting in typical "equilibrium alloys," as shown in Table 2.

Development work associated with the design and configuration of the fuel element has been directed almost exclusively to the problems associated with remote fabrication and assembly. These efforts have included development of precision-casting and assembly techniques, sodium bonding and remotely operated welding equipment. Prototype equipment has been built and is being tested under simulated operating conditions.

A similar development program is being conducted to fix the fabrication process for the EFFBR extruded fuel elements, including determination of billet configuration, billet-jacket dimensions and extrusion-process variables. The quality of the extrusion and the 0.004-in. clad thickness depend on the accurate control of these variables. In addition, the subsequent sizing operation must be carefully controlled, including the annealing steps. Finally, the stabilizing heat treatment of the finished fuel elements is essential to achieving irradiation-damage resistance.

Achieving a sound sodium bond in the EBR-II fuel element has been a more difficult problem than anticipated. The fuel element has a 0.006-in. annulus between the fuel pin and the fuel tube that must be filled with sodium and must be void-free. The most successful bonding technique has

TABLE 1—Fast-Reactor Chronology

Reactor	*Power [Mw(th)]*	*Operator*	*Date of operation*
Clementine	25 (kw)	LASL	1949
Dismantled			1953
EBR-I		ANL	1951
Mark III core			1957
Mark IV core			1959
EBR-II	62.5	ANL	1959
Dounreay	60	U. K.	1958
LAMPRE-I	1	LASL	1958
LAMPRE-II		LASL	
EFFBR	300	PRDC	1960

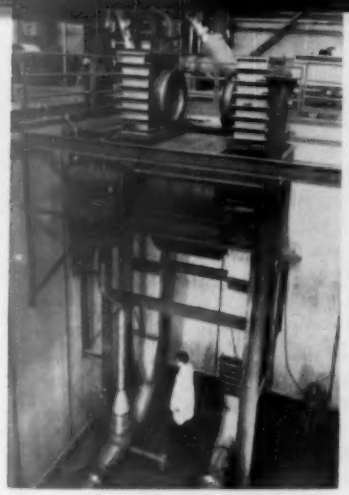


FIG. 1. Fast-reactor component progress is evidenced by large d-c electromagnetic sodium pump

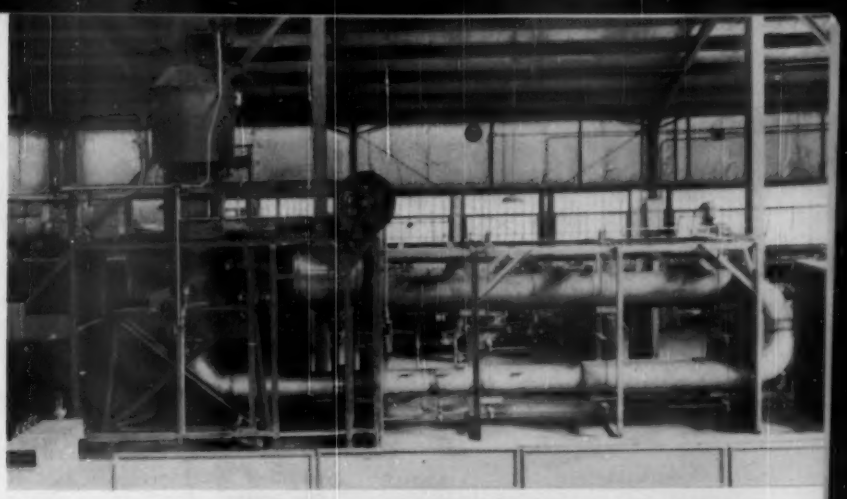


FIG. 2. Large (5,000 gmp) mechanical pump in place on sodium test loop. Pump has accumulated equivalent of more than eight months successful operating time

employed a high-temperature centrifuge, but this large and complex machine is not amenable to remote operation. Work is continuing on "pressure-pulsing" the molten bond to displace voids by applying alternately vacuum and pressure. The use of ultrasonic vibration to achieve a sound bond is also being investigated. Both techniques offer promise but to date have not been as successful as centrifuging. Nondestructive eddy-current testing of fuel elements, now developed to a high degree of accuracy, has been used to evaluate success of bonding techniques. It will also be used to test the finished EBR-II fuel elements.

An increasing effort is being applied to developing plutonium-uranium alloys. The immediate effort is being directed toward the second (plutonium) loading of the EBR-II, with the emphasis on U-Pu-fissium alloys. Results to date indicate that the EBR-II fuel-process cycle can be converted from enriched U to U-Pu with essentially no change in the cycle or equipment. Radiation-damage results indicate that the uranium-plutonium-fissium alloys are very stable in the range of 10–20% Pu in U. This particular range was selected for initial evaluation because it is the composition of interest for large, fast power reactors. The effect of "fissium" addition to the U-Pu binary system is shown very dramatically in Fig. 3.

Molten plutonium. The molten-plutonium fuel-development program for LAMPRE is quite different from the solid-element program because irradiation-damage and fuel-fabrication problems do not exist. Here the emphasis is on corrosion and materials.

Tantalum is receiving attention as a core-container material under the operating conditions to be met in LAMPRE. Tests conducted to date indicate that high purity is required in both the Pu and the sodium-coolant systems. The effects of impurities must be better understood, and whether an interrelationship exists between the systems must be determined.

To date, major emphasis has been on determining the effects of oxygen as

Nuclear Parameters for Fast and Thermal Power Reactors

Fast reactors are the only reactor type capable of breeding Pu from U^{238}. The breeding capability of a reactor system is influenced largely by the cross sections of the fissionable isotopes for the various interactions in the neutron spectrum existing in the system. For purposes of comparison, values for the pertinent nuclear parameters for the three fissionable isotopes in typical fast and thermal power reactors are given in the table below.

The parameters in the table below are given for a typical fast-reactor neutron spectrum and a thermal spectrum at 480° F (0.045 ev). The parameters are σ_f, the fission cross section; γ, the number of neutrons emitted per fission; η, the number of neutrons emitted per neutron absorbed ($= \gamma/(1+\alpha)$; α, the ratio of capture cross section to fission cross section.

The most significant parameter pertaining to breeding is η, while σ_f influences the reactor design. In a fast reactor, neutron efficiency is also enhanced by the low parasitic capture cross section of coolant, structure and fission products, and by fast fission of U^{238}. As a result, a breeding ratio of at least 1.5 is attainable in a practical fast Pu^{239}-U^{238} power-breeder-reactor system.

Parameter	U^{235}		U^{233}		Pu^{239}	
	Fast	Thermal	Fast	Thermal	Fast	Thermal
σ_f	1.5	430	2.3	400	1.7	700
γ	2.5	2.47	2.57	2.52	2.95	2.91
η	2.17	2.08	2.42	2.29	2.68	1.94
α	0.15	0.19	0.06	0.11	0.1	0.5

the contaminant. It is quite clear that oxygen must be maintained at extremely low levels in both systems. Mass transfer and the effect of oxygen have been studied in a simple tipping apparatus. An intermittent-tilting furnace pours the liquid Pu back and forth between the hot and cold ends of a welded capsule, allowing time for the melt to come to temperature at each end. Deoxidizing materials like Ca-Mg alloy have shown promise in this apparatus as mass-transfer inhibitors.

Considerable development is also required on tantalum production and fabrication. Procurement of suitable material has posed considerable difficulty so far.

Basic work is also required on various alloy systems of interest. LAMPRE-I will use the Pu-Fe eutectic alloy (Fig. 4). More dilute Pu alloys will be required for larger molten-Pu fast reactors. Other binary-alloy systems are under investigation, such as the Pu-Mg eutectic, which melts at 500° C and contains 85 atomic % Mg. In addition, ternary systems in which a third metal acts as a diluent with little effect on the melting point of a binary eutectic are under investigation.

Because molten fuel does not undergo radiation damage, fission products can accumulate to about 10% burnup before becoming objectionable as a fuel diluent. Thus, processing can be delayed and a process that would remove an appreciable portion of each fission product without significant Pu loss would be adequate to prepare the spent fuel for reuse. (At 10% burnup, the LAMPRE fuel contains: 2.75 wt % of the fission-product group containing rare gases, alkali metals, alkali earths and other active elements; 3.24 wt % rare earths; 3.76 wt % refractory metals; and 2.17 wt % Fe.)

However, fission gases can form bubbles in the liquid fuel. If the bubbles do not escape, the reactor would be shut down in a matter of hours. Scrubbing of the fuel inside the reactor with an immiscible molten metal is being studied as a possible means of removing fission gases as well as combined oxygen.

Oxides. Some preliminary work has been conducted with oxides, both U and U-Pu oxides, as potential fast-reactor fuels. Results have indicated that oxides may be able to sustain very high burnup.

Offsetting this advantage is their lower density. The diluent oxygen displaces fuel, structure or coolant and does not contribute to the system. (This is a particularly severe handicap in small reactors—EBR-II would be subcritical if the metal fuel were replaced with uranium oxide, even if fully enriched.)

In addition to the disadvantage of lower density, there is some concern over the thermal-expansion characteristics of oxides. The most important temperature effect in a fast reactor is the thermal expansion of the fuel, which provides a negative temperature coefficient responding instantaneously with reactor power. The thermal expansion of oxides is small and rather unpredictable, particularly after high burnup with consequent deterioration of the material. This characteristic raises some question with respect to reactor stability in the event of a power transient.

Oxide fuels have not been ruled out for fast reactors. However, at the present time they do not appear to have the advantages attributed to them for thermal, water-cooled systems.

In addition to solid-oxide fuels, investigation of UO_2-NaK suspensions was begun at ANL to develop a fluid fuel suitable for a fast reactor requiring a concentration of about 20 vol % (volume per cent) UO_2. Because of recent interest in dilute slurries for thermal reactors and because basic information can be obtained more readily from dilute slurries, most of the work has been with 5 vol % UO_2 in NaK. The slurries have been circulated for several hundred hours in loops at temperatures up to 650° C; they remained uniform in composition and neither eroded nor corroded the stainless-steel tubing of the loop. Pressure-drop measurements have also been made in these systems. Further, the UO_2 could be immediately resuspended after it had been permitted to settle out of suspension. The concentration limit of UO_2 in NaK has not yet been established; however, a slurry containing 15 vol % UO_2 in NaK has been circulated at temperatures up to 700° C and the slurry appeared to be uniform in composition.

The effect of fission products and radiation on the slurry rheology still remains to be determined. In addition, it would be desirable to extend the concentration to about 35 vol %, which is the approximate concentration

U. K. Fast-Reactor Program

The present U. K. program is based on the installation of natural-uranium, graphite-moderated, gas-cooled reactors with a total capacity of ~6,000 Mw by 1965. This program will produce ton quantities of by-product plutonium in the middle sixties. With the presently planned fuel burnup of 3,000 MwD/ton, ~2 kg of plutonium is produced per ton. If this can be improved to 5,000 MwD/ton, the plutonium produced will be increased accordingly. Under these conditions, however, only about 0.5% of the total fuel (U^{235} and U^{238}) is utilized. Recycle of the extracted Pu in thermal reactors may increase this to 3%.

It has been assumed in the U. K. that fast reactors of acceptable capital cost will not be constructed much before 1970. During the period 1970–80, the number of fast reactors built might be expected to increase rapidly until, in the 1980s, they may represent a major proportion of all new construction. Another study indicates that power costs should be approximately constant during the interim period (1970–80) and possibly decrease as fast-reactor technology improves.

In a system consisting mainly of fast reactors with high burnup, and a breeding gain equal to or greater than the rate of expansion of the system, fuel costs will represent only a very small fraction of the total cost of generating electricity.

To initiate this program, the U. K. has a 60-Mw(th) experimental fast power breeder reactor under construction at Dounreay in the North of Scotland. It will be fueled with 30%-enriched uranium metal and is scheduled to go critical in mid-1958. A turbine-generator will be installed in late 1958, and the plant will produce electricity although it is primarily a reactor experiment. It is planned to fuel the reactor with plutonium after an extensive program has been completed on the enriched-uranium loading. A prototype power reactor is planned for the late 1960s.

limit for a fluid slurry. It would also be desirable to extend the temperature-stability range so that the reactor structure and ancillary equipment, rather than the fuel, would set the temperature limit.

Data-Theory Correlation

Only recently have the needed experimental facilities (critical facilities and exponential facilities) become available to the experimentalist to produce data needed by the theoretician. Fast-reactor theory, with the aid of these tools, has now developed to where the theoretician can predict with reasonable accuracy the performance of fast-reactor systems and can guide engineering design of these systems.

The critical-experiment program is a continuing effort to obtain physics data, fundamental reactor data and engineering data. Physics data include a wide variety of nuclear parameters, e.g., Doppler temperature coefficient, neutron spectrum, neutron lifetime and geometrical effects.

Fundamental data are obtained from experiments on elementary assemblies (spheres, slabs and cylinders) uncomplicated by features present in actual power reactors. These experiments furnish data on critical mass, relative worths of reactor materials, axial-and-radial neutron-flux distributions and fission-to-capture ratios.

Engineering data are obtained from carefully simulated power-reactor configurations. These data are required for the detailed design of reactors and constitute nuclear proof tests of the reactor.

The critical experiments cannot duplicate all conditions that will exist in an operating power reactor. Temperature coefficient, power coefficient, reactivity changes with time and kinetic characteristics must be determined analytically. Suitable techniques have been developed for these analyses, and verification of the results obtained by critical experiments, where applicable, has improved accuracy of the analyses beyond the range of critical-experiment evaluation.

Component Development

The major effort in the development of system components for fast power reactors is directed toward sodium components, i.e., pumps, valves, piping systems and heat exchangers.

Although considerable advancement has been made in sodium-component technology in the past ten years, it is still a relatively new field, and the application of sodium as a coolant has not found wide usage.

FIG. 3. Irradiation results point up sharply beneficial effect of fissium (Fs) in fuel alloy. Alloy A had 11 % Fs, remaining samples none; burnup was greatest for A

Many types of sodium pumps have been built and operated successfully. However, whether electromagnetic induction, electromagnetic conduction, canned-rotor centrifugal, electromagnetic centrifugal or sump-type centrifugal, each has been designed to avoid using a moving sodium seal. It was long ago found that any direct seal would fail in an unreasonably short time. Besides the sealing problem, early workers in sodium pumping found that no conventional bearing would operate successfully in sodium. With special bearing materials and designs, it is now possible to operate centrifugal pumps with bearings submerged in sodium.

Just recently, centrifugal sodium pumps of practical size for power-reactor applications have been operated successfully with "hydraulic bearings." A photograph and drawing are shown in Figs. 2 and 5. A-c linear-induction type and d-c-conduction type electromagnetic pumps have also been developed in large sizes. Because they are completely sealed and have no moving parts, they are finding particular application where long-term leak-free, maintenance-free operation is required.

The first of the six pumps for the EFFBR has been completed. It is the largest pump ever constructed for sodium service, with a capacity of 11,800 gpm at a 310-ft head. It is a sump-type centrifugal pump with hydraulically balanced bearings and a hydraulically balanced volute configuration. This unit employs an oil-backed end-face seal between the inert-gas blanket and the atmosphere. Operational testing of this unit will be included in the nonnuclear test program scheduled for the test facility.

Similar progress is being made with electromagnetic pumps for sodium. A 5,000-gpm a-c linear-induction pump and 12-in. pipe loop have operated satisfactorily in excess of 6,000 hr at over 700° F. With minor modifications to the controlled-voltage power supply, it has been possible to achieve very fine flow control (increments of 1 gpm at low flow rates).

A large d-c, electromagnetic pump

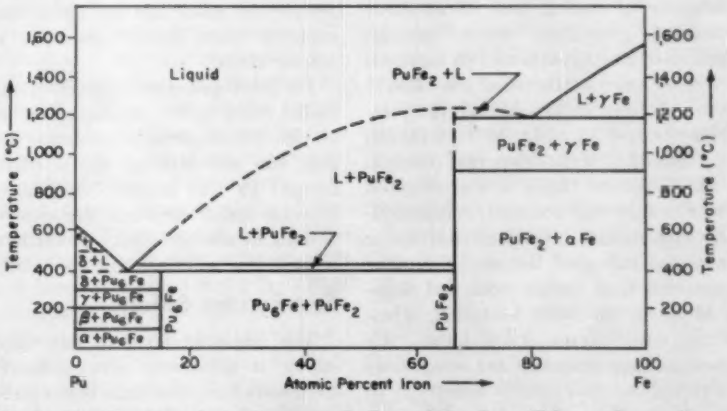


FIG. 4. Plutonium-iron phase diagram. Pu-Fe eutectic alloy will be used as molten fuel in LAMPRE-I

(Fig. 1) has just been placed into operation but has not yet reached its design capacity of 10,000 gpm at a 75-psi head. The d-c pump is the least temperature sensitive of the three types, and small models have been operated at temperatures over 1,500° F. The major difficulties with the large sizes are the very large currents required (250,000 amperes at 3 volts for this pump) and the problems

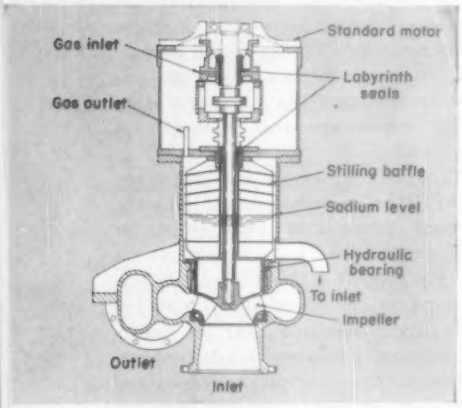


FIG. 5. Design of 5,000 gpm centrifugal sodium pump (shown in Fig. 2) using hydraulic bearing. Pump drove 12 in. diam sodium loop for more than 6,000 hr at head of 40 psi and sodium temperatures in excess of 700° F

associated with current sources and conductors.

Considerable difficulty has been encountered with mechanical components —control drives, fuel-loading systems, etc.—operating in sodium or sodium vapor. It has been necessary to modify conventional designs considerably for this service. The basic difficulty is associated with the very poor lubricity of sodium and its excellent cleaning properties, which enhance galling of mating surfaces. A mock-up (Fig. 6) was constructed of the EBR-II primary system to test various components and, in addition, to establish the feasibility of the submerged concept.

Development work is also required on new materials and their compatibility with sodium. Work already under way has indicated the need for other materials than carbon steels and stainless steels, including tantalum, zirconium, molybdenum and niobium. Although these materials are compatible with sodium, they exhibit sensitivity to oxygen in the sodium and perhaps to other impurities. It is unlikely that these "exotic" materials will be used extensively. It is necessary, therefore, to determine the effects of other materials in the system.

It is also necessary to determine the operational limitations of the common structural materials, such as low-carbon steels. Here, again, the evaluations must be made in terms of other materials in the same system. For example, a specific problem that must be resolved is the compatibility of carbon steel and stainless steel in a sodium system at high temperature; carbon steel is decarburized while the stainless steel is carburized, and sodium appears to be an excellent vehicle for the carbon. If this is a serious problem, the limiting sodium temperatures and oxygen concentrations must be determined.

Fuel Reprocessing

Fuel reprocessing development in conjunction with the fast-reactor development program has been directed toward the nonaqueous or pyrometallurgical processes. These processes offer considerable promise of reduced fuel-reprocessing costs through: (1) simplicity, (2) plant compactness, (3) reduction of fuel inventory through ability to process short-cooled material, (4) retention of expensive alloying constituents and (5) production of waste fission products in concentrated form suitable for economic utilization or storage.

These processes are particularly applicable to fast-reactor fuels because fission products have small capture cross sections in a fast-neutron spectrum and incomplete fission-product removal does not affect reactivity. This permits achieving small fuel inventory by quick fuel cycling in small-capacity units located close to the reactor plant.

For heterogeneous, metal-alloy, solid-fueled reactors, the emphasis has been on the development of oxidative slagging for melt-refining the irradiated metal. In this process, volatile and gaseous fission products are evolved, and highly reactive fission products are removed by reaction with the crucible.

Fast-Reactor Safety

The major problem in fast-reactor safety is accidental core meltdown. To resolve this problem, a better understanding is required of fast-reactor kinetic characteristics and instabilities. At the present time, EBR-I is being used to obtain such data. A new core, strongly instrumented for temperature measurements, is now in operation, replacing the previous core, which was damaged during similar experiments. The new core consists of rod-type fuel elements tightly packed in hexagonal fuel assemblies to limit mechanical motions of the core during power operation. This added rigidity is expected to depress the positive temperature coefficient and improve the dynamic stability. Provision is also made for permitting series or parallel coolant flow through the inner blanket and core of the new assembly, providing flexibility of operation.

An understanding of core meltdown is required because the collapse of the core upon itself might increase the reactivity enough to cause a nuclear burst. Although the EBR-I core did melt without these results, it has not been established that this is impossible.

To specify the course of such an accident it is necessary to know the history of uranium motion in time and space until resolidification has occurred. This involves such things as sodium boiling, the interaction of molten uranium with clad and structure and the refreezing of uranium during a time- and space-dependent heat input.

Some theoretical analyses of simplified models of the accident have been made. While they throw valuable light on the course of events, they

TABLE 2—Calculated Equilibrium Composition of Fissium* (Based upon 5 Weight % Process Addition/Cycle)

Element	*Enriched uranium*	*U-Pu alloy*
Zirconium	0.10	0.08
Niobium	0.01	0.01
Molybdenum	3.42	3.15
Technetium	0.99	0.96
Ruthenium	2.63	3.48
Rhodium	0.47	0.60
Palladium	0.30	1.35
Total fission elements	7.91	9.67
Balance:		
Uranium	92.09	70.33
Plutonium		20.00

* Fissium is the name given to the equilibrium mixture of fission products that will remain in the fuel after many process cycles.

demonstrate a clear need for experimental information to provide insight into the mechanisms of failure and the probable behavior of the core following overheating. Except for the accidental meltdown of the EBR-I Mark II core, however, there have been only a few experiments on electrically heated dry pins and some tests involving the fluidity of molten uranium to guide theoretical studies.

Fuel-element test facility. There is currently under construction a nuclear transient-test facility to study the transient behavior of fast-reactor fuel elements up to, through and beyond failure. This facility, named TREAT, is actually a thermal reactor into which large power bursts can be introduced safely. The test sample will be overheated under controlled conditions with various instruments reporting on the course of events. With this facility it should be possible to melt an enriched-uranium fuel element or cluster of fuel elements cooled by stagnant or flowing sodium on reactor periods of 20 msec or longer and to study the course of failure as a function of materials, material history and operational conditions.

Nuclear burst analysis. A theoretical exploration of the characteristics of low-order nuclear bursts is also planned. The determination of the possible energy yields and pressures resulting from various configurations will provide a guide for reactor design and containment specifications.

Analyses of this type have been performed on very simple systems and correlated with experiment. These calculations have been coded for an IBM-704 calculator and have been tested by matching the results of prompt excursions with the Los Alamos Godiva assembly. The calculations and the experiments, in general, compare satisfactorily.

Calculations have been extended to unreflected uranium systems of lower U^{235} enrichment than Godiva. For these assemblies, critical mass and delayed critical multiplication measurements are available, but prompt-burst experiments have not been made.

Advanced Concepts

LAMPRE-I, the first test of the Los Alamos molten-plutonium concept, will be followed by a much larger experiment intended to incorporate as many as possible of the features needed in a full-size power plant. LAMPRE-II will be a flexible facility with provisions for substitution of alternate core designs. Included will be an integral fuel-handling and processing plant and a uranium breeding blanket.

A general study of coupled fast-thermal systems has been under way at ANL for over a year. The major advantage over the "all-fast" system is a substantially longer prompt-neutron lifetime, which is achieved with only a small reduction in breeding ratio. Efforts to date have been primarily exponential and critical experiments on the general characteristics of fast-thermal systems and feasibility studies.

The system currently believed to be the best possibility consists of a fast core surrounded by an inner blanket containing natural U, Na coolant and structural material, but no moderator; beyond this is a Be moderator and beyond that is an outer blanket of depleted U. The inner blanket serves the multiple purposes of core for the thermal system, reflector for the fast core and barrier for low-energy neutrons between the moderator and the fast core. Thermal fissions in the inner blanket arise from neutrons that have been thermalized in the Be. The system is about 5% subcritical without the contribution of thermal fissions. The neutron lifetime is in the thermal range (approximately 2×10^{-5} sec), and the breeding ratio is reduced about 10% from the all-fast system.

The above configuration appears suitable for both full-scale systems and also EBR-II sized systems. Critical experiments on coupled systems the size of EBR-II are now in progress.

It is not believed that any major engineering problems will be encountered with this system that differ from those faced in the case of the all-fast system or sodium-cooled thermal reactors. The immediate objectives are to establish definitely the feasibility of the concept and to obtain a detailed conceptual design of the reactor system.

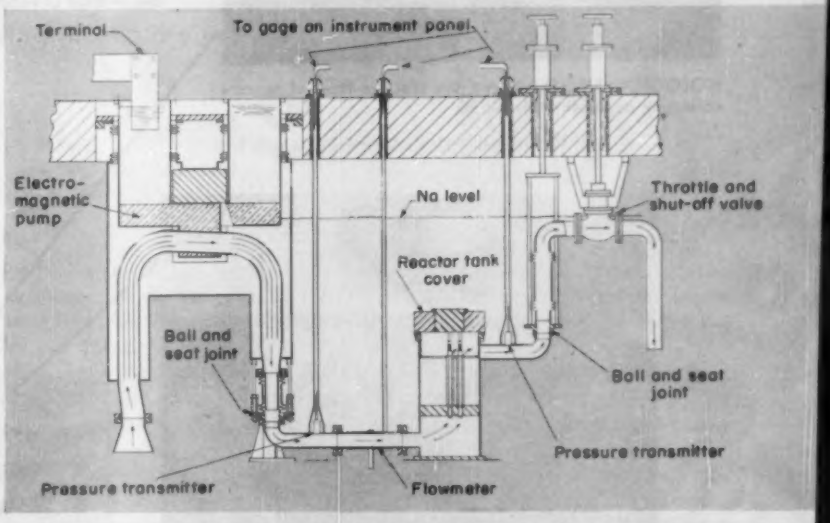


FIG. 6. Mock-up of EBR-II primary system contains 5,000 gal of sodium electrically heated to 700° F. It contains essential mechanical components (scaled downed), including complete fuel-transfer system and control drive. Modified pumping system has 1,000-gpm capacity. Experiment has operated satisfactorily for over 2½ yr

The primary incentive for this extensive development program is utilization of uranium resources. The fast breeder appears to be potentially the most efficient reactor type to accomplish this.

The same utilization will be required of our thorium resources if they are to make a sizable contribution to the world's energy demands. For the present, it is believed that the U^{233}-thorium breeder cycle can be accomplished with thermal reactors. However, this has yet to be demonstrated—fast reactors may be required to achieve efficient utilization of thorium as well.

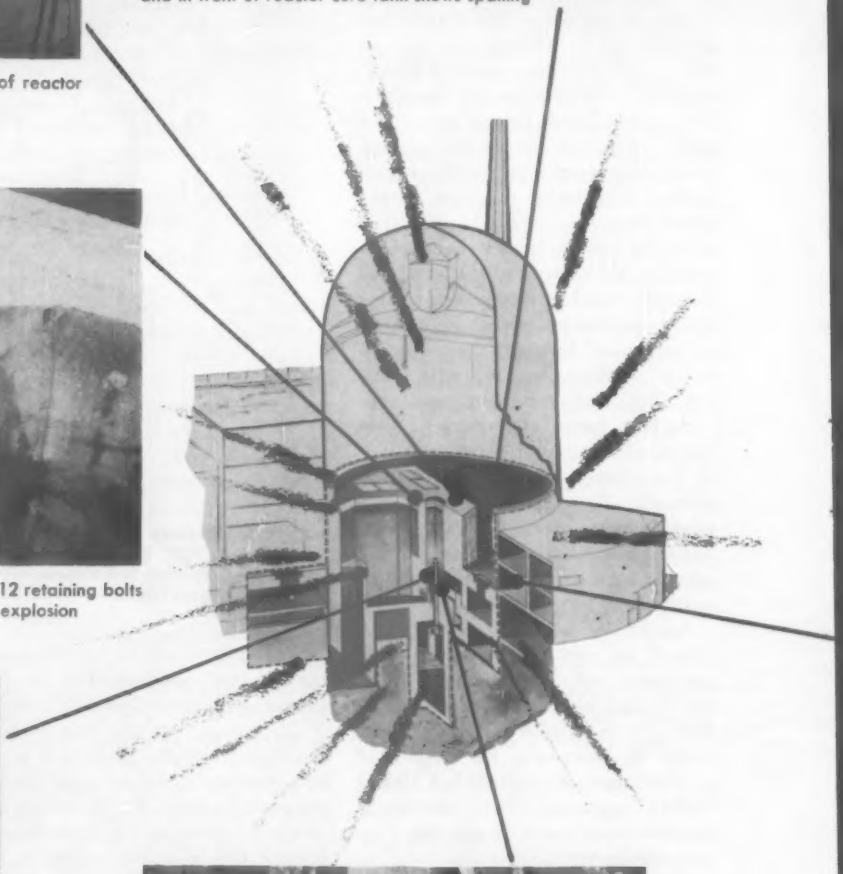
• • •

This article is based on the work of many people—far too many to recognize individually. The author wishes to express his appreciation to all of them, in particular members of the staffs of Los Alamos Scientific Laboratory, the Power Reactor Development Company, Atomic Power Development Associates and Argonne National Laboratory.

REINFORCED-CONCRETE structure above thermal column and in front of reactor core tank shows spalling

BIOLOGICAL SHIELD suffered this crack in front of reactor core tank as result of Round 10

REACTOR TANK LID is ajar after 10 out of 12 retaining bolts gave way during 1,000 Mw-sec Round 10 explosion



CORE CENTER SECTION as viewed from bulk shield tank after Round 5 (67 Mw-sec)

CORE CENTER SECTION as viewed from bulk shield tank after Round 10 shows core mock-up disappeared

Simulating Nuclear Blast Effects

Charges were set off to mock up nuclear excursions in a ¼-scale reactor model. Damage suffered by the model indicates that the full-scale design can safely contain energy releases exceeding that in the maximum credible accident

By JAMES R. BOHANNON, Jr. *United States Air Force, ARDC, Wright Air Development Center, Dayton, Ohio*
and WILFRED E. BAKER *Aberdeen Proving Ground, Aberdeen, Maryland*

CONTAINMENT SHELL SUPPORT of test model was breached by final and largest internal explosion

SINCE the Air Force Nuclear Engineering Test Reactor (AF NETR) (*1*) is to operate in a populated area (Wright Air Development Center, Dayton, Ohio), the design philosophy has, from the start, been to ensure absolute containment of all activity released by the maximum credible nuclear excursion. The Borax experiments can be used to predict the magnitude and rate of such an excursion in an MTR-type reactor such as AF NETR. However, at the time AF NETR was being designed there was little experience that could be used to predict the effect of such an energy release on the reactor structure and safety shell. Although theoretical analyses on the effects of internal blasts on containment structures have been performed, seldom is the geometry so simple that conservative simplifying assumptions (and consequent overdesign) can be avoided.

Therefore the AF NETR project office concluded it was necessary to evaluate experimentally the effects of a power excursion on the reactor structure of the size predicted by Borax test data. It was concluded (*2*) that a *geometrically scaled model* subjected to internal blast from a similarly *geometrically scaled explosive charge* should suffer the same damage as would be expected for the full-scale reactor.

A one-quarter scale model of the reactor building within the safety shell was selected based upon the limits of scaling, costs, construction difficulties, and model workability. Blast test on the model showed that the design structure can be considered safe for energy releases exceeding that expected in the maximum credible accident. Design changes based on the test results were incorporated to make the structure even safer.

Test Procedure

Millisecond-period reactor excursions were simulated in the test model by firing appropriate charges (ranging from relatively slow-burning propellants up to explosives comparable to TNT) at the reactor core position. In all, ten simulated excursions were conducted, beginning with an equivalent energy release of 26 Mw-sec and concluding with a 1,000 Mw-sec shot. For the larger energy releases only explosives were used because of the lack of space for placing the charge as well as the limited time available for developing firing and handling techniques for the propellant.

Measurements were made of the time variations of the pressure, strains, displacements, and accelerations at various locations within the model. All firing had high- and normal-speed motion picture coverage. After each detonation, an observation of the damage resulting from the firing was made. Attention was given to the directions of structural failures and pressure releases, the maximum energies imparted to both the reactor shield and structural components capable of acting as missiles and the existence of sustained static overpressures in confined areas.

Scaling

Applying the test-model results to the full-scale design involves three assumptions: (a) reactor power bursts are realistically simulated by explosive and propellant charges, (b) the model is an adequate mockup of the full-scale system, and (c) scaling laws hold for blast effects. A discussion of the validity of these assumptions is on page 78.

As to (a), a nuclear power excursion is characteristically exponential in form. An explosive is essentially a step release of energy with an associated shock wave while propellants produce significant pressure rises in the media without a shock wave. The latter, therefore, would more closely simulate energy release of a nuclear power excursion or

Summary of Test Results

Round number	Kind of simulation	Energy release (Mw-sec) Actual	Full-scale equivalent
1	Propellant	0.404	26.0
Damage limited to center core tank section.			
2	Propellant	1.47	94.1
Damage more severe than Round 1, but limited to immediate vicinity of core center. Shielding in thermal column displaced about 6 in.			
3	Propellant	4.34	278
Damage to all sections of core tank severe. Simulated graphite window displaced into bulk shield facility about ¾ in., flooding of test cells and basement. Shielding in thermal column displaced length of column and impinged on doors, displacing roll door 1 in. Test cell roll doors displaced several inches. (Roll doors were free to move on casters.)			
4	Explosive	0.336	21.5
Damage to core tank severe. Graphite window into bulk shield crushed, but not displaced. Shielding in thermal column displaced length of column. Thermal column roll door displaced 2½ in. Both test cell roll doors displaced about 1½ in. (Damage about equivalent to Round 3.)			
5	Explosive	1.05	67.2
Damage to core tank severe. Graphite window into bulk shield facility crushed, and upper half projected into pool, resulting in very rapid flooding of test cells. Thermal column roll door displaced 8¾ in., with 3.9 ft/sec maximum velocity. Test cell roll doors displaced about 1½ in.			
6	Explosive	3.15	202
Damage to core tank more severe than Round 5. Graphite window into bulk shield facility completely demolished and projected into pool as small fragments. Thermal column roll door displaced 45 in., with maximum velocity of 18.8 ft/sec. West test cell roll door displaced 13 in., east one 12 in. First damage to fixed parts of model occurred, with extensive hairline cracking of concrete adjacent to core tank. Equipment room west of bulk shield facility flooded to 5 in. depth by pipes from test cell.			
7	Explosive	6.31	404
Severe damage to core tank. Ten of twelve bolts holding top plug fractured or stripped threads in nuts, and projected upward with velocities up to 35.6 ft/sec. Plug lifted about 6 in., and returned, held by two bolts. Damage to graphite windows same as on Round 6. Thermal column roll door driven length of its tracks, with maximum velocity 27.8 ft/sec, impinging on outer wall. Cracking of concrete adjacent to core tank severe, necessitating repair before remaining firings.			
8	Explosive	0.336	21.5
This round was a repeat of Round 4. Damage was nearly identical.			
9*	Propellant	3.09	198
Damage intermediate between that of Rounds 2 and 3.			
10	Explosive	15.64	1,000
Very severe damage to core tank. Ten of twelve bolts holding top plug fractured, and projected upward with velocity of 130 ft/sec. Some welds in test cell assembly broken. Thermal column roll door driven length of its tracks and impinged on wall, initial velocity 41.0 ft/sec. West test cell roll door blown off tray, against outer wall, and badly cracked. East test cell roll door driven against wall. Movable bridge over bulk shield facility thrown up and over south lip of model. Damage to fixed parts severe, with cracks up to 2 in. in width near core tank. Outer wall breached in one place and displaced outward about ½ in.			

* Results of this round should be disregarded, since the propellant did not burn completely.

chemical explosion (e.g., aluminum-water reactions). In any case, Borax data indicate that the energy release rate in a nuclear power excursion is much slower than for either explosives or propellants. Thus the use of explosives and propellants in these tests is believed to produce *"conservative"* results—i.e., the damage should exceed that in the real situation.

Test Results

Specifically the explosives showed (*2*) essentially step increases (within a few microseconds) to maximum pressure. The propellant mixtures were an order of magnitude slower (0.05–0.9 msec). For a Borax-type burst (*3*) 80% energy release would be completed in about 1.5 msec in the model or 6.0 msec in the prototype.

In the construction of the model (see p. 74) all structural concrete surrounding the core and major appurtenances such as walls, slabs and footing were made as nearly identical to the prototype as was practical. The model did not include the safety shell since it would be of no experimental value* and would only interfere with camera observations. Within practical limits, components likely to become missiles were simulated. Scaling factors were used in all details, e.g., the sizing of aggregate, reinforcement rods and placement of structural penetrations. All materials and their densities and elastic and plastic properties were made as identical to the prototype as possible. Certain variations from the prototype were made in the model to test proposed design changes. These included the shaping of the irradiation test cell shield down doors as trapezoidal sections to allow early venting of the cells, integral floors and walls, unkeyed construction joints connecting the periphery wall with the biological shield and the bolting of the top plug to the reactor tank.

Scaling considerations (*2*) resulted in the following ground rules. Strain-time and pressure-time histories in the full-scale design can be derived from the model results by maintaining amplitudes constant and expanding times by a factor of four. Masses projected out in the actual reactor will have the same initial velocities as found in the model. For energy release compari-

* Damage to the safety shell, if any, could be predicted from observed damage to the outer perimeter of the model structure.

son, a 1,000 Mw-sec excursion in the prototype can be simulated by a 238-kg C-3 explosive charge. The *geometrically scaled charge* simulating this excursion in the one quarter scale model would weigh 3.7 kg.

Comparison of the results from the propellant and explosive releases shows a strong dependence of damage on rate of energy release. Round 3, with a full-scale energy equivalent of 278 Mw-sec released relatively slowly by a propellant, produced damage about equivalent to Rounds 4 and 8 in which explosives released full-scale energy equivalents of only 21.5 Mw-sec.

Concrete parts subjected to large strains showed extensive cracking, splitting and some spalling while all-steel parts whose strains exceeded elastic limits were distorted but intact.

The pressure impulses in the underwater parts of the model were only one-tenth to one-third as great as those expected of pure underwater blast. By contrast, the test doors and thermal columns, which were relatively free-air areas, showed appreciable increases in loadings compared with pure free-blasts. These results clearly indicate that the energy from the explosion was effectively "vented" from the core to the air volumes with a corresponding reduction of underwater blast loads on other parts of the model.

Since no appreciable long-time pressure rises showed up in the subpile or equipment rooms, pressure escape from the core tank, test cells and bulk shielding facility was quite low. Blast pressures in Round 10 (1,000 Mw-sec full-scale equivalent) escaping the surface of the bulk shielding facility were only 0.6 psi in amplitude.

The first visible damage to the bulk structure around the reactor core occurred in Round 6—a full-scale reactor excursion of 202 Mw-sec simulated by an explosive. This damage consisted only of hairline cracks in the concrete next to the core tank, a slight movement of the thermal column door and the blowout of the graphite window into the bulk shielding facility. Containment was not compromised. No damage, other than hairline cracks, occurred to the basement floor or interior of the subpile room.

In Round 7 (404 Mw-sec full-scale equivalent) a slight widening of the cracks from Round 6 were noted together with a greater movement of the thermal column door and graphite window. In addition, ten of the twelve bolts holding the top plug of the reactor tank fractured or stripped their threads. Again this damage would not have compromised containment in the full-scale design. Round 7 exceeded the total energy release predicted by the Borax experiment analysis (*3*).

Round 10, the final and largest of the blasts, caused damage severe enough to endanger reactor containment. The concrete wall that supports the upper containment shell at the first floor level was breached and displaced about half an inch. Even so, because of the structural weakening of the model by Round 7, one can argue that the results of Round 10 were extremely conservative and would not have compromised containment.

Conclusions

The test results lead to the conclusion that, with minor modifications in its design, the AF NETR containment structure can be considered *reasonably safe* for energy releases up to 1,000 Mw-sec. This is approximately three times the maximum energy release in the maximum credible nuclear power excursion for the NETR.

The most important of the modifications is the incorporation of a shock break gap at the intersection of the east wing wall and the circular outer wall between the basement floor and the first floor east of the reactor core. The gap is designed to prevent direct transmission of a blast shock from the wing wall to the periphery wall. Minor changes include the elimination of bolts in the top plug that might act as missiles, securing the thermal column door, providing a position holddown for the instrument bridge over the BSF, venting of the basement area to prevent overpressures exceeding the designed working pressure of the tunnel doors, and the placing of a steel face over the reactor biological shield to eliminate spalling or missile effects.

There is no doubt that the structure will be very much safer than necessary, and would probably contain a nuclear excursion several times the total energy release of 1,000 Mw-sec because of the drastically reduced damaging capabilities of the relatively slow nuclear excursion compared with explosives.

* * *

The continued assistance of Messrs. Eric Wang and J. C. Noble and Lieutenant R. J. Mayerjak of the Effects Division of the Air Force Special Weapons Center–ARDC to the Air Force Nuclear Engineering Test Facility project office in the planning and review of the tests is gratefully acknowledged.

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2. Wilfred E. Baker and James D. Patterson, II Blast effects tests of a one-quarter scale model of the Air Force Nuclear Engineering Test Reactor, BRL Report 1011 (March 1957)
3. J. R. Dietrich, Experimental investigation of the self-limitation of power during reactivity transients in a subcooled, water-moderated reactor, AECD-3668 (1955)

AEC Containment Studies

Although the AF NETR model tests gave useful information for that particular design, everyone agrees that extrapolating the results to other reactors would be risky. In contrast the AEC's program in this area is geared to produce fundamental containment data that would be useful for whole reactor families. The major AEC contracts for this work are held by:

Naval Ordnance Laboratory, White Oak, Maryland, is conducting static and dynamic tests on water-filled steel and stainless-steel cylinders to determine optimum containment design for reactor pressure vessels.

The Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, is continuing experiments to assess the blast resistance of vapor containment shells of reactors. Model tests are designed to assist in developing scaling laws for such structures.

Stanford Research Institute, Menlo Park, California, is studying containment of missiles which may result from a core vessel explosion.

Armour Research Foundation, Chicago, Illinois, is doing theoretical and experimental work in containment, especially relating to the design of blast shields as a device for attenuating effects of an excursion.

Argonne National Laboratory is initiating a study of containment philosophy and practice in relation to research and power reactors. From this study will come a clearer picture of the "state of the art," including economics of containment.

For comment on this article turn page ➡

Comment on "Simulating Nuclear Blast Effects" (P. 75)

Using the blast tests on the model to draw conclusions about the safety of the full-scale reactor is justified only if one is convinced that the explosive and propellant charges provide reasonable imitations of a nuclear excursion and that the blast damage does, in fact, obey the suggested scaling laws. That opinion on these points is somewhat divided can be seen from the following comments supplied to NUCLEONICS by other people in the field.

Comment by
F. B. Porzel
(Armour Research Foundation)

• The authors describe a worthwhile experiment on an over-all test of reactor containment designed against chemical-type explosions. However, since the reactor was designed before the test occurred, it is almost a tautological remark that the design must have leaned heavily on theoretical considerations. Because the damage was approximately as expected from theoretical considerations, I believe that the tests are therefore a comforting corroboration of the theoretical concepts and that, despite the necessity for "conservative and simplifying assumptions," the theory evidently does not result in the excessive overdesign.

Considerable caution must be exercised in interpreting the effects of scaling in general and, in particular, the effect of the duration of the energy release. Close to the source, an explosive release of short duration will produce higher pressures than an explosion of long duration. However, at long enough distances, all the energy from the explosion must eventually appear as "waste heat" produced by the entropy change across the shock front. This "waste heat" is in turn a strong increasing function of the pressure in the shock. If the pressures are low near the charge, the dissipated heat is correspondingly low. Hence, it is always true that "far enough out" the energy available from a slow reaction will be larger than the energy available from fast reaction; as a result, the peak pressures from the slow reaction will be higher.

Unfortunately, the point at which the curves cross is most likely to be found near the "dynamic crushing strength" of the material. Beyond this the wave is essentially elastic and because the pressure may be quite high there may still be danger of structural failure. In some typical explosive media, a short duration explosion may dissipate 99% of its energy before the pressures fall to levels which can be controlled by structural design, whereas a long duration explosion may have dissipated only a small fraction of its energy at the same distance. Thus the propellant is efficient at relatively low pressures—like pushing a projectile out of a gun tube—in contrast, an explosive is efficient at high pressures—like shattering a shell case.

The results from the experiment described can only be interpreted as follows. Evidently, the damage observed and evaluated by the author was at pressure levels high enough so that the pressure-distance curve from the propellant was still below the pressure-distance curve from the explosive; the test results at these distances should then be conservative compared with a slower rate of energy release. However, at larger scale distances, in other media, or in terms of damage from impulse criteria, the propellant will produce larger damage than explosives; test results from TNT would not be conservative for low pressure damage from a slower chemical explosion.

The peak pressure distance curve is so enormously dependent on the geometry and type of media that each reactor will probably always have to be designed on its own merits. Once a reasonable design is made, as was done here, the test of a quarter scale model is appropriate to be certain that "no unseen giants" have been overlooked in the design. However, such tests will always be more a proof of a specific design than a means of providing design criteria for other situations: different geometry, absorbing media, pulse durations or vastly different explosion releases.

Comment by
R. W. Deuster
(Babcock & Wilcox)

• I am first concerned with the statements about geometric scaling. The argument for scaling is correct only as long as the elastic limits of the material are not exceeded. H. N. Brown, the author of an appendix to the original report, points this out, but the article fails to mention it. Brown further states that for the plastic flow regions, scaling is approximately true if the strain rate is not too large. Of course, one can accept these premises, but if one actually is dealing with strong shocks as a result of explosive chemical reactions, then the materials *are* plastically deformed, the strain rates are *too* large and the scaling goes to pot! Therefore, only at distances from the source of the shock where the elastic limits of the materials are not exceeded, can scaling give accurate results.

The second point I would like to comment about is the statement that "the use of explosives . . . . would produce 'conservative' results." While I tend to agree in general with this idea, I do not feel the experiments have proven this result. I call your attention to Porzel's analysis* of chemical reaction rate, where he states that "inhibition of the reaction is untrustworthy as a safety precaution alone unless the time of energy release be lengthened at least to a considerable number of seconds." One of the reasons for citing this precaution is that the strength of the shock and the nature of the deformation characteristics of the material absorbing the shock must be considered. What may appear to be a correct analysis for one shock strength and material need not be the case for another combination.

* ARF No. D090 (June 21, 1956).

J. R. Bohannon, Jr.

W. E. Baker

The Authors Reply to Porzel . . .

Porzel states that "the design (of the AF NETR) must have leaned heavily on theoretical considerations (of blast-resistant design)." First, the design was based primarily on the functional requirements of the reactor itself and on the considerations of biological shielding for protecting operating personnel. These features alone assumed proportions which appeared to be capable of resisting a blast comparable in magnitude (total energy wise) to the maximum credible incident. In addition, those features of the design which related directly to blast resistance, such as the trapezoidal shape of the outer test cell doors, the keyed or shock-break joints and shelf-type floors, were included in the model on an intuitive basis rather than on theoretical considerations of the response to blast loading. (The geometry was considered too complex for rational blast-resistant design.) Therefore the tests should not be considered as "a comforting corroboration of the theoretical concepts (of blast-resistant design)," as Porzel suggests. Instead, they provide evidence that this specific reactor design was blast-resistant enough to ensure containment of all activity released even under the most violent power excursion credible in the reactor.

Porzel's remarks on the effects of energy available from a slow reaction being greater than that from a fast reaction "far enough out" from the source are quite correct. However, it is believed that his suggestion that the pressure-vs-distance curves for a slow reaction and for a fast reaction cross near the dynamic crushing strength of the material thru which the shock is transmitted is not corroborated by the results of these tests. If his suggestion were true, the energy released by the propellant bombs would always have produced greater pressures and more damage to the model than equivalent explosively-released energy, since pressures during all tests were below the dynamic crushing strength of the material everywhere in the model except in the immediate vicinity of the core. Exactly the reverse was true; the pressure and damage were greater for explosives than for equivalent propellants.

There is other evidence that the cross-over of the peak pressure for slow and fast reactions occurs quite far from the energy source. H. L. Brode† compares the air blast waves from an explosive source to that from a sphere of high pressure gas, suddenly released. The pressure from the sphere of gas lies well below that from the explosive out to over-pressures of 10 psi. Therefore, Mr. Porzel's statement, "test results from TNT would not be conservative for low pressure damage," is only correct if the structure is so weak that it will suffer significant damage from very weak shocks. The authors feel that their conclusion that slower energy release rates are less damaging than rapid ones, and that an explosive will consequently produce conservative safety test results, is quite valid.

† *J. Appl. Phys.* **26**, No. 6, 766 (June, 1955).

. . . And to Deuster

Mr. Deuster is quite correct in his remarks that elastic response of the structure was presumed in the analysis of structural response scaling, given as Appendix I in reference (*2*), which formed a basis for the tests. However, it has become apparent from other analyses that the presumption of elastic response is not required for validity of geometrical scaling. Perhaps it should be mentioned that "geometrical scaling" implies that all characteristic dimensions of both the structure and the explosive loading source are reduced by the same scale factor in the model, while all material properties are maintained constant. Although scaling of plastic structures is difficult to demonstrate without resorting to some rather involved mathematics, perhaps an example of the response of one structural element will suffice to show this fact.

The permanent deformation of a "rigid-plastic" beam subjected to blast loading has been predicted by F. J. Allen and F. Rally.‡ A simply-supported beam is assumed to be rigid under blast loading until a critical bending moment is reached at some cross-section, at which time the beam "hinges," or plastically deforms, until the moment drops below the critical value. The permanent deflection of the center portion of such a beam subjected to a blast load of peak over-pressure P and duration T is given by:

$$y = \frac{bP}{A\rho}\left(\frac{\lambda^2}{2} - \frac{\lambda^3}{6T}\right) + \frac{12A\rho M_0}{(bPT)^2} \ln \cos\left[\frac{(bPT)^2}{12A\rho M_0}(x-1)\right]$$

In this expression, b = beam width, ρ = beam material density, A = beam cross-section area, M_0 = critical moment, l = beam length, x = distance from beam center and

$$\lambda = \frac{bPl^2}{12\,M_0}\,T$$

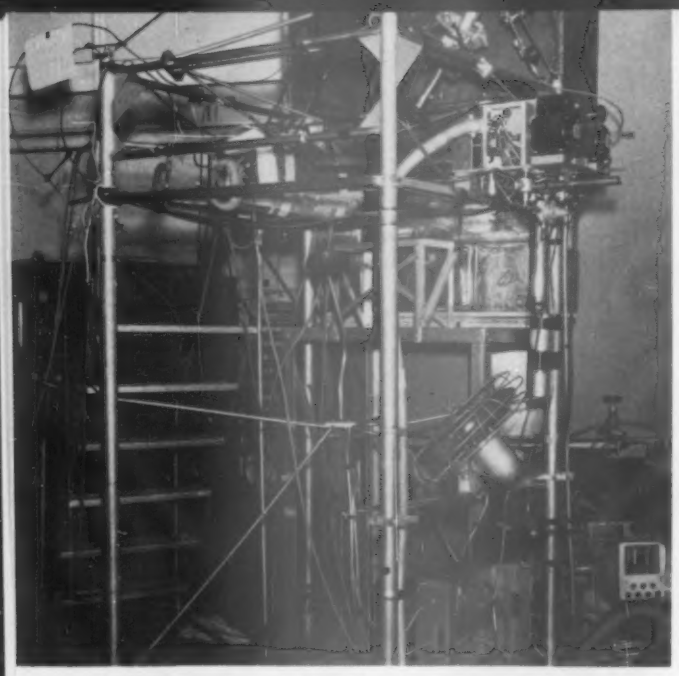
The deformation of a similar beam with all dimensions scaled by factor k, caused by a scaled blast load of peak over-pressure P and duration $T' = kT$, will now be computed. For the model, $b' = kb$, $x' = kX$, $l' = kl$, $A' = k^2A$, $M_0' = k^3M_0$, $\lambda' = k\lambda$. Substitution of these scaled values in the above equation yields the result that $y' = ky$, or that the deflection of the model is just k times the deflection of the original beam. Therefore, geometrical scaling holds for this plastic response model.

Geometrical scaling has also been found to hold for the response of an "elastic-plastic" spherical shell to internal blast loading, and for other simpler elastic-plastic response problems. (In elastic-plastic response problems, the material is assumed elastic until yield stress is reached, at which time plastic flow is assumed until rupture occurs or motion stops.)

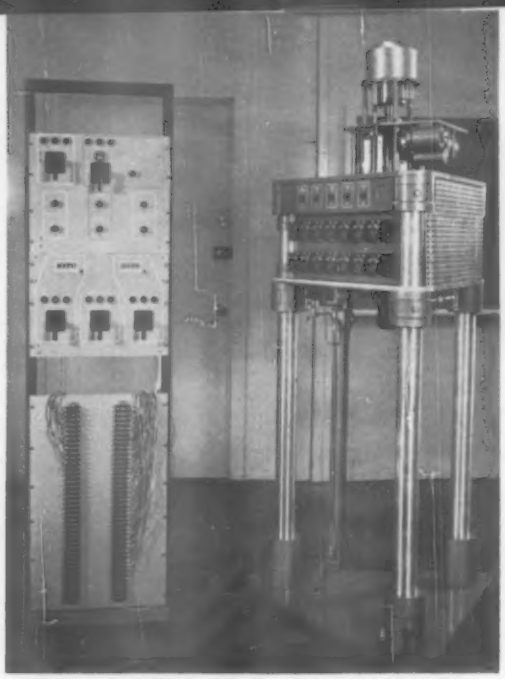
Furthermore, an empirical fragmentation law tells us that the initial velocity of fragments from the casing of an encased explosive charge is a function of a single parameter, the ratio of weight of explosive charge to weight of casing. If we geometrically scale such a charge, this ratio remains constant and the fragment velocity is unchanged, which agrees with our premise of scaling of structural response.

It therefore appears likely that the geometrical scaling employed for the AF NETR model tests is valid for quite large strain rates, for materials deformed plastically, and even for materials deformed to rupture.

‡ A plastic-rigid theory of the response of beams to air blast loading, BRL Memo. Report No. 811 (July, 1954).



Between this (Godiva I, after accident) . . .



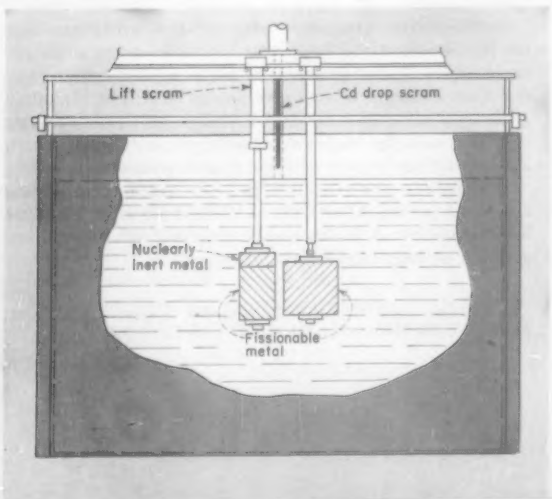
and this (Godiva II), lie many . . .

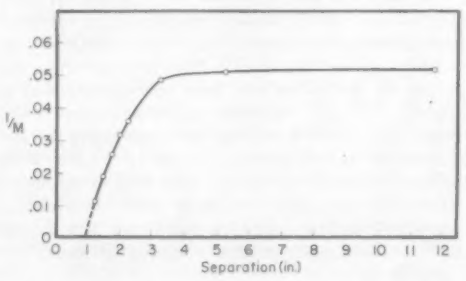
Critical-Assembly Booby Traps

By HUGH C. PAXTON *Los Alamos Scientific Laboratory, Los Alamos, N. M.*

1. Unanticipated motions in scram can cause burst

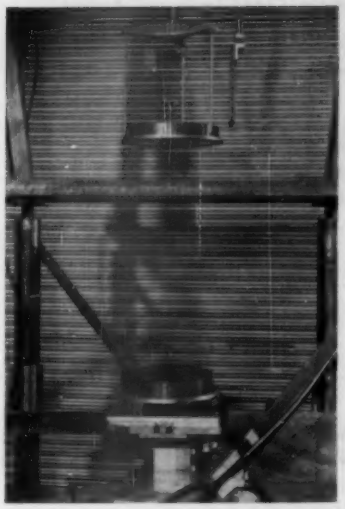
A modification to our water-reflected oralloy assembly The Aquarium (below, left) resulted in our first remote, accidental burst. Designed originally for determining the neutron multiplication of a single piece of fissionable metal in water, it included, as one scram, a pneumatic cylinder that raised the unit out of the water. A traveling support and a second unit was added, so that distances between two units could be determined, and a dropping Cd screen was provided as an additional scram. When scrammed, local radiation detectors went off scale and a cloud of steam showed on the monitoring television screen. Reconstruction showed that the pneumatic scram was the first to be effective and led to two types of difficulty: (a) the center of reactivity of the left hand cylinder was below that of the stationary cylinder, and (b) the rapid lift through the water brought the two cylinders together. The total burst of $\sim 10^{17}$ fissions probably came from several independent bursts separated by bubbling. The well-known sensitivity of systems like this to separation as the critical value is approached makes it easy to be misled by extrapolation of the reciprocal multiplication curve (below, right) in evaluating the safety of a next step.

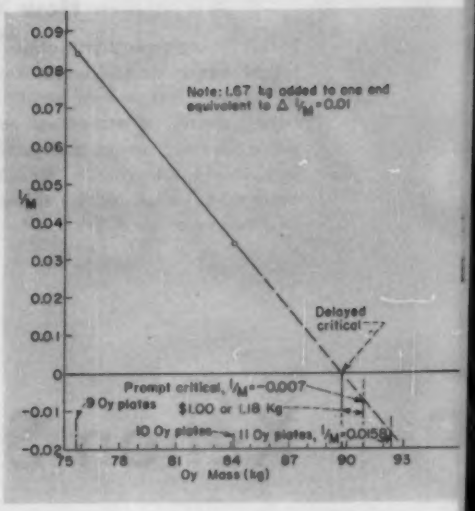




2. Human error in calculating criticality

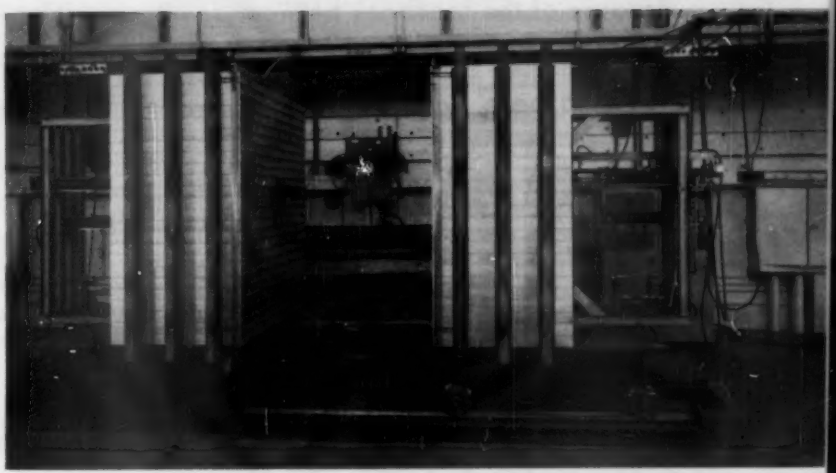
At right is Jemima, another assembly with which we had trouble—this time arithmetic. During buildup to delayed critical, indication that an added plate of enriched uranium would make the system supercritical by a certain margin was erroneously interpreted as meaning that it was subcritical by that same margin. A too-rapid assembly (even though controlled increments were available) led to a burst of 7×10^{16} fissions but no damage. A plot of the data (far right), omitted in this case even though called for by our operating regulations, could hardly have been misinterpreted, but sure enough it was.




Note: 1.67 kg added to one end equivalent to Δ 1/M = 0.01
1/M
Delayed critical
Prompt critical, 1/M = -0.007
9 Oy plates
$1.00 or 1.18 Kg
10 Oy plates
11 Oy plates, 1/M = 0.0158
Oy Mass (kg)

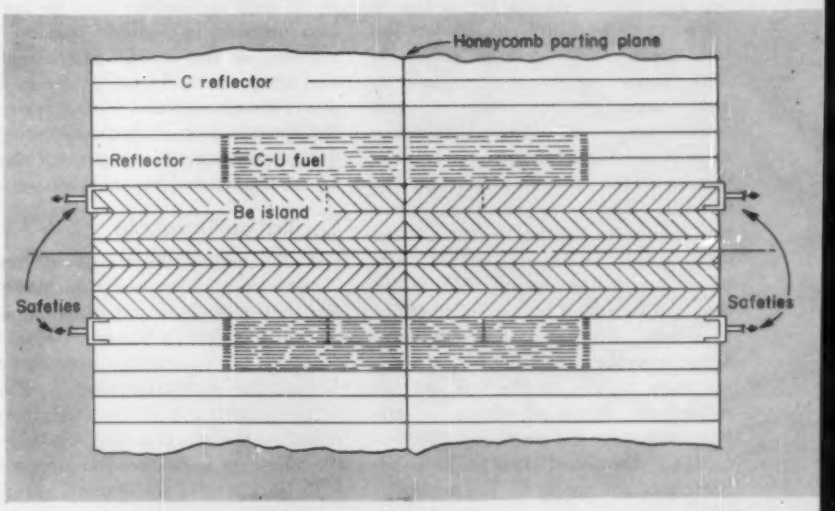
3. Too-rapid approach to criticality

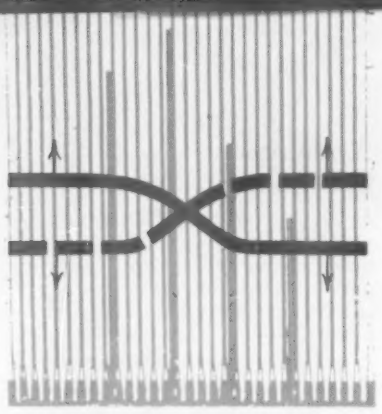
In our Honeycomb assembly (right), we had a burst for which we still can find no clear stopping mechanism other than the relatively sluggish scrams. Here, the active region was formed by long sandwiches of enriched-uranium foil (0.005 in. thick) and graphite that slipped into Al matrix tubes. Too large a change in the core, and incautious assembly, led to a burst of 3×10^{16} fissions. The initial part of the assembly motion was fast, the final part slow, and the system became critical before the slow range was reached—but the foils were not damaged.



4. A near miss— "safeties" weren't safe

Apparently innocuous changes in an assembly can have very surprising effects. In another Honeycomb assembly (lower right), a potentially risky situation could easily have developed had we not been feeling our way carefully and deliberately. Evolution had led from an assembly containing thin Be islands, in which withdrawal of Be and fuel proved most effective safeties, to this assembly, in which the first 6 in. of "safety" motion (simultaneous withdrawal of Be and fuel rods) gave a 30-cent reactivity *gain*. Within this range the fuel rods were ineffective and the Be made a positive reactivity contribution.





How Xenon Oscillations Arise

Initial tilt in power distribution (solid curve, first diagram) causes tilt of xenon poison concentration (dotted curve) in opposite direction. This in turn amplifies power tilt (second diagram). Later, decay of stored-up xenon precursors reverses xenon curve, causing power distribution to tilt in other direction (third and fourth diagrams). Resultant power oscillation will continue unless stopped by differential motion of control rods in two halves of core

Xenon Spatial Oscillations

Because of the feedback between reactor power and xenon production rate spatial oscillations in power can exist even though total power is constant. To avoid these, designers should provide independent control of local regions

By D. RANDALL and D. S. ST. JOHN
Savannah River Laboratory, E. I. du Pont de Nemours & Co., Inc., Aiken, S. C.

A LARGE THERMAL REACTOR operating at sufficiently high flux levels is subject to oscillations in the power distribution that are associated with a periodic redistribution of xenon poison. Consider a reactor operating at constant total power and at xenon equilibrium. The introduction of a small tilt in the flux shape, for example from top to bottom, causes the xenon to burn out more rapidly at the top and less rapidly at the bottom, while the local rates of formation of xenon from iodine decay remain nearly constant for some time. The reactivity increases then at the top of the reactor and decreases at the bottom, amplifying the flux tilt. The power peak at the top of the reactor is limited by the control devices that maintain constant total power, and by the amount of reactivity that can be added by the burning out of xenon. Ultimately the growth of xenon from the iodine that is now forming more rapidly at the top and the radioactive decay of xenon at the bottom reverse the reactivity distribution, and the power then peaks in the bottom of the reactor. These oscillations persist unless control poisons are moved so as to counteract them.

Xenon oscillations can occur only at high flux levels, at which the rate of xenon burnout is important relative to the rate of xenon decay, and in large reactors, in which small local changes in reactivity result in extended changes in the power distribution. The possibility of such oscillations must be taken into account in hazards studies for reactors of this kind. Instrumentation adequate to detect changes in the power distribution and control systems flexible enough to allow the operator to flatten power peaks can prevent damage to the reactor from this source.

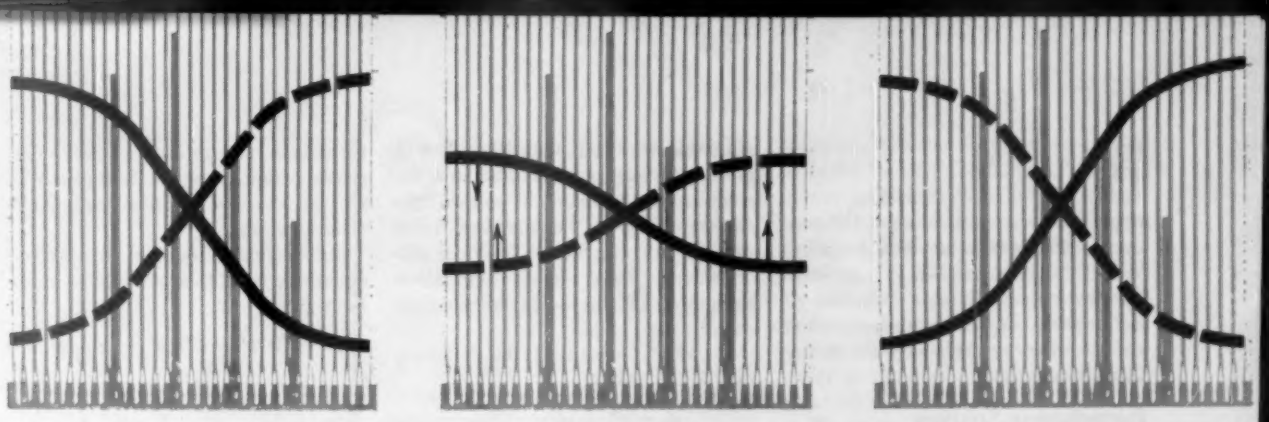
Oscillation Threshold

Xenon oscillations can persist only above a threshold value for the neutron flux that depends mainly upon the size and the flux distribution of the reactor. Ward (*1*) has presented a perturbation method for computing this threshold for power distributions that are proportional to the fundamental solution of the boundary value problem associated with the shape of the reactor. Henry and Germann (*2*) have considered the special case of two reactors coupled by a diffusing medium. This model allowed them to solve the nonlinear pile equations on an analogue computer without considering the detailed flux distribution.

We have extended the perturbation method of Ward to reactors with power distributions that differ significantly from the fundamental shapes and have developed methods that predict the oscillation threshold with a minimum of computation. These considerations lead to the following simple recipe for estimating the oscillation threshold in a reactor with an arbitrary power distribution.

The threshold for oscillations in the jth mode of the flux distribution is given by the average flux level, ϕ, that satisfies

$$\left(\frac{M^2B_g^2}{\alpha_x}\right)\Lambda_j - \frac{\alpha_T}{\alpha_x}\phi = f(\phi) = \frac{1}{1+\lambda_x/\sigma_x\phi} - \gamma_x \Big/ \frac{1+(\lambda_x+\lambda_i)/\sigma_x\phi}{}$$



α_x is the reactivity held by xenon at very high flux, M^2 is the migration area, B_g^2 is the geometrical buckling, and α_T is the temperature coefficient, expressed in terms of reactivity per unit flux. The function, $f(\phi)$, depends only upon the decay constants of Xe^{135}, λ_x and of I^{135}, λ_i; the fraction γ_x of Xe^{135} formed directly from fission rather than through I^{135} (which fraction is denoted by γ_i), and the xenon cross section, σ_x. Figure 1 shows $f(\phi)$ for the value of σ_x that is quoted in the table. Figure 1 can be used for any other value, σ_x', by multiplying the ordinate, ϕ, by σ_x/σ_x'.

The dimensionless parameter, Λ_j, depends only upon the shape of the flux distribution and is equal to the difference between the eigenvalue of the jth mode of the flux distribution and the eigenvalue of the fundamental mode, divided by the geometrical buckling.

The procedure for estimating the oscillation threshold is to compute Λ_1 by one of the three methods listed below, to multiply this by $(M^2B_g^2/\alpha_x)$, to subtract (α_T/α_x) times an estimated flux threshold, and to look up the threshold flux from Fig. 1. This value can then be used to improve the term containing the temperature coefficient in the next iteration.

• For a reactor that has a flux distribution equal to the geometrical mode, the eigenvalues of the modes of the flux are identical with those of the geometry. In the case of a cylindrical reactor, the flux distribution and the geometrical buckling are both separable into an axial and a radial component and the threshold for oscillation can be estimated for each component separately. The axial component of the flux distribution is sinusoidal and the fundamental eigenvalue is $(\pi/H)^2$. The higher eigenvalues are $(j+1)^2(\pi/H)^2$, so Λ_1 is three, Λ_2 is eight, and so on. The radial component has a fundamental eigenvalue of $(j_{0,1}/R)^2$, with higher eigenvalues equal to $(j_{n,i}/R)^2$, so $\Lambda_{1,1}$ is 2.539 and $\Lambda_{0,2}$ is 5.269. Usually only the lowest value of Λ concerns us. This simple estimate of Λ_1 is adequate to show that most small research or package power reactors are too small to maintain xenon oscillations.

• For power distributions that do not differ greatly from the fundamental geometric mode (i.e., the flux is flat in no more than the central 40% of a linear dimension), it is fairly accurate to assume that the higher eigenvalues of the flux modes are identical with those of the geometrical boundary-value problem. For this case

$$\Lambda_j = \frac{1}{B_g^2}\left(\kappa_j^2 - \frac{\int B^2 f_j^2\, dV}{\int f_j^2\, dV}\right)$$

where κ_j^2 and f_j are defined by

$$\nabla^2 f_j + \kappa_j^2 f_j = 0$$

with the f_j satisfying the same boundary conditions as the flux. For a sinusoidal flux shape, $\kappa_j = (j+1)B_g$, and $f_j = \sin(j+1)\dfrac{\pi h}{H}$.

• For flux distributions that differ substantially from the fundamental geometrical distribution Λ_j is found from

$$\nabla^2 g_j + B^2 g_j + \Lambda_j B_g^2 g_j = 0$$

where B^2 is the space-dependent material buckling that determines the unperturbed power distribution in the hot, poisoned reactor. The flux distribution $g_0(\Lambda_0 = 0)$ can be determined by iteration techniques for which high-speed computer codes exist. Modification is required to adapt these codes to determine Λ_1 and g_1.

For a three-dimensional reactor, oscillations can occur about any axis. The lowest Λ must be determined for each mode from the appropriate g_j. As an example, we consider a cylindrical reactor with a flat power distribution. Here g_0 is a constant, Λ_0 is zero, and B_g^2 is $(\pi/H)^2 + (j_{0,1}/R)^2$. For axial oscillations, $g_{1,0}$ is $\cos(\pi h/H)$ and $\Lambda_{1,0}$ is $(\pi/H)^2/B_g^2$. For oscillations about a diameter, $g_{0,1}$ is $J_1(1.841\, r/R)\cos\theta$, and $\Lambda_{0,1}$ is $(1.841/R)^2/B_g^2$ [1.841 is the lowest x for which $J_1(x)$ is a maximum]. If the height of the cylinder is equal to its diameter, $\Lambda_{1,0}$ is 0.299 and $\Lambda_{0,1}$ is 0.411. As the average flux level is increased, axial oscillations would be encountered first. If these oscillations were suppressed by suitable control-rod motions, and the power raised still further, oscillations about a diameter would start.

Mathematical Formulation

Since the xenon oscillations are expected to occur only in large thermal reactors, the distribution of thermal flux can be treated by one-group diffusion theory

$$\nabla^2\phi + B^2\phi = 0 \qquad (1)$$

where ϕ is the neutron flux and B^2 is the space- and time-dependent material buckling of the hot, poisoned pile. Equation 1 implies that the oscillations are slow compared with the effects of the delayed neutrons, so that at any time the flux shape is determined primarily by the spatial distribution of B^2. As shown by Ward (*1*), the period of the xenon oscillations is 20–30 hr.

The equations governing the concentration of Xe^{135} at any point in the reactor are

$$\frac{di}{dt} = \phi\sigma_x\gamma_i - \lambda_i i$$

$$\frac{dx}{dt} = \phi\sigma_x\gamma_x + \lambda_i i - \lambda_x x - \phi\sigma_x x \quad (2)$$

where i is the concentration of I^{135} relative to the equilibrium concentration of Xe^{135} that is reached at very high flux levels; x is the concentration of Xe^{135} relative to its saturation value; and the other symbols have the meanings given earlier.

Perturbation Solution

Ward (*1*) assumed small perturbations and linearized Eqs. 1 and 2 to determine the oscillation threshold (near which the assumption of small perturbations is a good one). His method of solution is repeated here with two modifications. The effect of power coefficients is included and the solutions are expanded in terms of the eigenfunctions of the boundary value problem for the actual buckling distribution. These modifications allow estimation of thresholds for practical cases.

To start, substitute the following into Eqs. 1 and 2

$$\begin{aligned} \phi &= \phi^* + \phi' \\ B^2 &= B^{2*} + a_T\phi' + a_x x' \\ x &= x^* + x' \\ i &= i^* + i' \end{aligned} \quad (3)$$

where the starred quantities are solutions of the unperturbed equations, the primed quantities are small perturbations, and a_T and a_x are coefficients that express the dependence of B^2 on changes in flux and Xe^{135} concentration.

Subtracting the original unperturbed equations from this new set of equations gives

$$\nabla^2\phi' + B^{2*}\phi' + \phi^* a_x x' + \phi^* a_T\phi' = 0$$

$$\frac{di'}{dt} = \phi'\sigma_x\gamma_i - \lambda_i i' \quad (4)$$

$$\frac{dx'}{dt} = \phi'\sigma_x\gamma_x + \lambda_i i' - \lambda_x x' - \phi^*\sigma_x x' - \sigma_x x^*\phi'$$

The time derivatives in Eqs. 4 can be eliminated by searching for solutions of the form

$$\begin{aligned} \phi' &= \phi'' e^{\omega t} \\ x' &= x'' e^{\omega t} \\ i' &= i'' e^{\omega t} \end{aligned} \quad (5)$$

Substituting into Eqs. 4 yields

$$\nabla^2\phi'' + B^{2*}\phi'' + \phi^* a_x x'' + \phi^* a_T\phi'' = 0$$

$$\omega i'' = \phi''\sigma_x\gamma_i - \lambda_i i'' \quad (6)$$

$$\omega x'' = \phi''\sigma_x\gamma_x + \lambda_i i'' - \lambda_x x'' - \phi^*\sigma_x x'' - \sigma_x x^*\phi''$$

Flux-Shape Eigenfunctions

The perturbation amplitudes of Eqs. 5 can be expanded in terms of the orthonormal eigenfunctions, g_i, of the boundary-value problem that has the unperturbed flux shape as its fundamental solution.

$$\begin{aligned} \phi'' &= \sum_i A_i g_i \\ x'' &= \sum_i X_i g_i \\ (\nabla^2 + B^{2*})g_i + \mu_i^2 g_i &= 0 \end{aligned} \quad (7)$$

Here μ_0 is zero and g_0 is proportional to the unperturbed flux.

After eliminating the iodine terms from Eqs. 6, substituting Eqs. 7 in Eqs. 6, multiplying by g_j, and integrating over the reactor volume, we have

$$(-\mu_j^2 + a_T\bar{\phi}_j)A_j + a_x\bar{\phi}_j X_j + \sum_{i\neq j}(a_T\bar{\phi}_{ij}A_i + a_x\bar{\phi}_{ij}X_i) = 0$$

$$\sigma_x\left(\bar{x}_j - \gamma_x - \frac{\lambda_i\gamma_i}{\lambda_i + \omega}\right)A_j + (\omega + \lambda_x + \sigma_x\bar{\phi}_j)X_j + \sum_{i\neq j}(\sigma_x\bar{x}_{ij}A_i + \sigma_x\bar{\phi}_{ij}X_i) = 0 \quad (8)$$

where $\bar{\phi}_j = \int\phi^* g_j^2\,dV$, $\bar{\phi}_{ij} = \int\phi^* g_i g_j\,dV$, $\bar{x}_j = \int x^* g_j^2\,dV$, $\bar{x}_{ij} = \int x^* g_i g_j\,dV$.

How to Prevent Oscillations

Xenon-induced oscillations in the power distribution can exist only in reactors that (a) operate at flux levels where xenon burnup is appreciable and (b) have "large" cores—cores having a linear dimension whose square is larger than the neutron migration area by a factor of 1,000 or so. This last requirement can be easily checked by remembering that the square of the linear dimension in feet must exceed the migration area in cm² for oscillations to occur. Thus in a light-water reactor with M^2 of 50 cm², we would worry about oscillations if one of the dimensions of the core were 7 ft or longer.

Physically this means that oscillations of this kind are possible when the core gets so large that two or more regions begin to function as independent nuclear units—i.e., hardly any of the fissions in one region are caused by neutrons born in the other region. The extreme example of this would be two identical reactors operating side by side which are cooled in parallel by a single coolant circuit and controlled by two central control rods ganged to move together. If the rods are used to hold the temperature of the outgoing coolant (and therefore the total power) constant, then, by the mechanism discussed in the first paragraph in the article, a slight initial fluctuation in the relative power outputs of the two reactors will lead to oscillations in the power levels of both reactors, one 180° out of phase with respect to the other.

The solution to the problem in this extreme example would be to measure the exit temperature of each reactor separately and move each control independently. Since the periods of these xenon spatial oscillations are of the order of one day, one could then easily suppress them with this arrangement. The corresponding solution for a single large reactor is to provide a power monitor and reactivity control in each independent region. Thus for a light-water reactor 5 ft in diameter and 100 ft long, we would need to worry about each 7-ft section and would place flux monitors and control rods every 3½ ft along the length. This would enable us to detect any incipient power distortion and trim to a constant power along the length of the system. In a reactor large in all dimensions, monitors should be on a three-dimensional lattice with a 3½-ft pitch, and the control system should be flexible enough to control the power at each monitor.

To avoid this difficulty entirely a large reactor must have either a very large negative temperature coefficient or a low flux level. It would be more economical in almost any case to design for the detection and control of incipient oscillations than to design around them altogether.

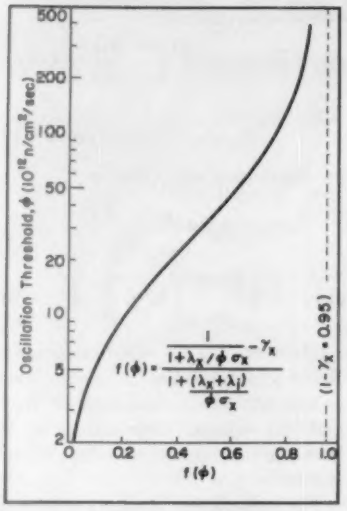


FIG. 1. Plot of threshold flux for xenon oscillation vs. $f(\phi)$ is used with Eq. 10a to find threshold for given reactor

Equations 8 form a homogeneous linear set for the unknowns, A_i and X_i. The requirement that the determinant of the coefficients be zero defines possible values of ω. The cross terms, $\bar{\phi}_{ij}$ and $\bar{x}_{ij}$, are small because of the orthogonality of the g_i's and are equal to zero if the unperturbed flux distribution is flat. If we make the approximation that the cross terms are zero, the possible values of ω are defined by

$$\omega^2 + b\omega + c = 0$$

with

$$b = \lambda_i + \lambda_x + \sigma_x\bar{\phi}_i - \frac{a_x\sigma_x\bar{\phi}_i(\bar{x}_i - \gamma_x)}{(-\mu_i^2 + a_T\bar{\phi}_i)} \tag{9}$$

and

$$c = \lambda_i\left[\lambda_x + \sigma_x\bar{\phi}_i + \frac{a_x\sigma_x\bar{\phi}_i(1-\bar{x}_i)}{(-\mu_i^2 + a_T\bar{\phi}_i)}\right]$$

The threshold for sustained oscillations is given by the condition that the damping term b is zero. When b is negative, the reactor is above the threshold. The condition that b is zero can be written in the form

$$\mu_i^2 = -\frac{a_x(\bar{x}_i - \gamma_x)}{1 + \frac{\lambda_i + \lambda_x}{\sigma_x\bar{\phi}_i}} + a_T\bar{\phi}_i$$

$$\equiv -a_x f(\bar{\phi}_i) + a_T\bar{\phi}_i \tag{10}$$

The eigenvalues, μ_i^2, defined in Eqs. 7, depend only upon the flux shape and pile size, while the right-hand side of Eq. 10 depends primarily upon flux level and only secondarily upon flux shape. If we combine the factors that depend upon the particular reactor, and substitute $\Lambda_i = \mu_i^2/B_g^2$, $a_x = \alpha_x/M^2$, and $a_T = \alpha_T/M^2$, Eq. 10 can be written

$$f(\bar{\phi}_i) = \frac{M^2B_g^2}{\alpha_x}\Lambda_i - \frac{\alpha_T}{\alpha_x}\bar{\phi}_i \tag{10a}$$

In Eq. 10a, B_g^2 is the geometrical buckling of the pile, α_x is the reactivity held by saturated xenon, M^2 is the migration area, and α_T is the power coefficient in terms of reactivity change per unit flux.

Figure 1 shows a plot of the function

$$f(\phi) = \frac{\frac{1}{1 - \lambda_x/\sigma_x\phi} - \gamma_x}{1 + \frac{\lambda_x + \lambda_i}{\sigma_x\phi}}$$

where $f(\phi)$ is the $f(\bar{\phi}_i)$ of Eq. 10 with the approximation that $\bar{x}_i$ is equal to $1/(1 + \lambda_x/\bar{\phi}_i\sigma_x)$, the steady-state value of xenon for a flux $\bar{\phi}_i$. This approximation is good since $\bar{\phi}_i$ and $\bar{x}_i$ as defined by Eqs. 8 are averages taken over the same weighting functions. Values of the constants used in computing the curves in Fig. 1 and subsequent figures are listed in the table.

Since $f(\phi)$ depends on σ_x only through the product, $\sigma_x\phi$, Fig. 1 can be used for a different value of the xenon cross section, σ_x', by multiplying the ordinate by σ_x/σ_x'.

The function, $f(\phi)$, is negative below the flux level of 3.5×10^{11} n/cm^2 sec at which the burnout of xenon is just equal to the direct formation from fission. Below this flux level, xenon instability cannot exist for a reactor of any size. The value of $f(\phi)$ increases monotonically with flux level and saturates at high flux to the value $(1 - \gamma_x)$, or to about 0.95.

Equation 10a shows the effect of the power coefficient, α_T, on the threshold. A positive power coefficient lowers the threshold for instability, and, if large enough, can cause oscillations in the power distribution without the aid of the xenon. A negative power coefficient, on the other hand, raises the instability threshold, and, if large enough, can eliminate the possibility of xenon oscillations altogether. For small negative coefficients, Eq. 10a has two solutions for the flux, representing the lower and upper bounds of the region of instability. The upper bound arises from the fact that xenon burnout saturates while the effect of the power coefficient does not, so that even a small negative power coefficient will give stability at very high flux levels.

Figure 2 shows the values of Λ_1, equal to μ_1^2 as defined by Eqs. 7 divided by the geometrical buckling, computed for a one-dimensional pile of height H (Λ_1' is defined in the next section). A series of symmetrical flux shapes was assumed with a region of constant flux in the center and a region of uniform buckling giving a sinusoidal flux shape at each end. Degrees of flatness all the way from a pure sine shape to a perfectly flat shape were considered.

Figure 3 shows the oscillation thresholds for these flux shapes as a function of the size of the pile, measured by the ratio H^2/M^2, which is equal to $\pi^2/$

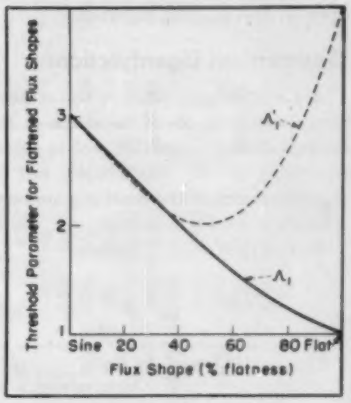


FIG. 2. Values of parameter Λ_1 to be used in Eq. 10a to find threshold flux

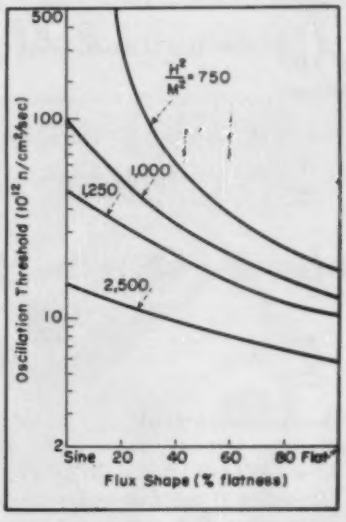


FIG. 3. Threshold flux vs. flux shape for different reactor size (H^2/M^2) and zero power coefficient

Constants Used in Calculations

$\lambda_i = 0.10584\ \text{hr}^{-1}$
$\lambda_x = 0.0756\ \text{hr}^{-1}$
$\sigma_x = 3.08 \times 10^{-18}\ \text{cm}^2$
$\gamma_x = 0.0487$
$\alpha_x = 0.0368$
$\alpha_T = 0$

$M^2B_g^2$. The power coefficient was taken to be zero.

While the foregoing procedure gives accurate results, it requires a knowledge of the functions, g_i, which are orthogonal to the actual flux distribution. For an arbitrary flux distribution, obtaining these functions requires computing machinery. In some cases, existing computer codes that are used to obtain the flux distribution, g_0, by relaxation or numerical integration techniques can be modified to converge upon g_1 and give its eigenvalue.

Geometrical Eigenfunctions

A great simplification in the computation can be made if the shape of the perturbation is expanded, not in eigenfunctions of the flux shape, but in eigenfunctions of the reactor geometry, which are readily available.

In this case, Eqs. 7 become

$$\phi'' = \sum_i A_i' f_i$$
$$x'' = \sum_i X_i' f_i \qquad (7')$$
$$\nabla^2 f_i + \kappa_i^2 f_i = 0$$

For a one-dimensional reactor, for example, $\kappa_i = (i+1)\pi/H$, and $f_i = \left(\frac{2}{H}\right)^{1/2} \sin\ (i+1)\pi z/H$. Eqs. 8 become

$$(-\kappa_j^2 + \bar{B}_j^2 + a_T\bar{\phi}_j')A_j' + a_x\bar{\phi}_j'X_j' + \sum_{i\neq j}[(\bar{B}_{ij}^2 + a_T\bar{\phi}_{ij}')A_i' + a_x\bar{\phi}_{ij}'X_i'] = 0$$

$$\sigma_x\left(\bar{x}_j' - \gamma_x - \frac{\lambda_i\gamma_i}{\lambda_i+\omega}\right)A_j' + (\omega + \lambda_x + \sigma_x\bar{\phi}_j')\bar{X}_j' + \sum_{i\neq j}(\sigma_x\bar{x}_{ij}'A_i' + \sigma_x\bar{\phi}_{ij}'X_i') = 0 \qquad (8')$$

where $\bar{\phi}_j' = \int\phi^* f_j^2\,dV$, $\bar{\phi}_{ij}' = \int\phi^* f_i f_j\,dV$, $\bar{x}_j' = \int x^* f_j^2\,dV$, $\bar{x}_{ij}' = \int x^* f_i f_j\,dV$, $\bar{B}_j^2 = \int B^{2*} f_j^2\,dV$, $\bar{B}_{ij}^2 = \int B^{2*} f_i f_j\,dV$.

Equation 8′ contains cross terms in the buckling, $\bar{B}_{ij}^2$, that do not appear in Eq. 8. For a reactor with a flux shape equal to the geometrical mode, B^{2*} is a constant, and Eqs. 8′ and 8 are identical. However, for a flat flux shape, B^{2*} is large near the edge of the pile and small near the center, and the cross terms become increasingly important. Thus, more terms in the expansions of the shape of the perturbation [Eqs. 7 and 7′] must be carried with Eqs. 8′ than with Eqs. 8, to give the same accuracy.

For reactors with flux shapes that do not differ too much from the geometrical shape, we can neglect the cross terms in Eqs. 8′ and get equations analogous to Eqs. 9 and 10.

$$\omega^2 + b'\omega + c' = 0$$

$$b' = \lambda_i + \lambda_x + \sigma_x\bar{\phi}_j' - \frac{a_x\sigma_x\bar{\phi}_j'(\bar{x}_j' - \gamma_x)}{(-\kappa_j^2 + \bar{B}_j^2 + a_T\bar{\phi}_j')} \qquad (9')$$

$$c' = \lambda_i\left[\lambda_x + \sigma_x\bar{\phi}_j' + \frac{a_x\sigma_x\bar{\phi}_j'(1-\bar{x}_j)}{(-\kappa_j^2 + \bar{B}_j^2 + a_T\bar{\phi}_j')}\right]$$

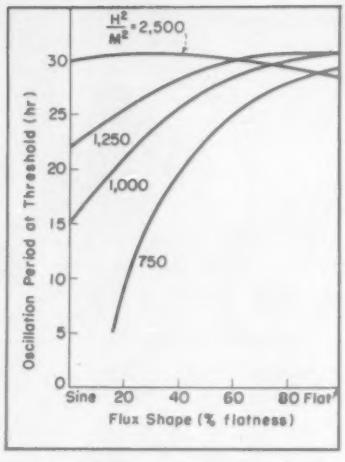


FIG. 4. Oscillation period vs. flux shape for reactors of different sizes with flux thresholds given in Fig. 3

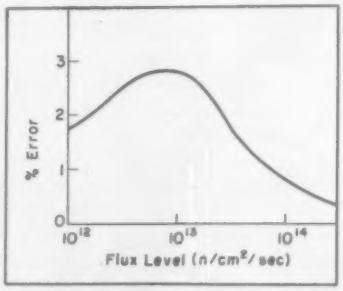


FIG. 5. % error in $f(\phi)$ in replacing $\bar{X}_1$ by $1/(1+\lambda_x/\sigma_x\phi)$

and

$$\kappa_j^2 - \bar{B}_j^2 = -\frac{a_x(\bar{x}_j' - \gamma_x)}{1 + \frac{\lambda_i+\lambda_x}{\sigma_x\bar{\phi}_j'}} - a_T\bar{\phi}_j' \equiv -a_x f(\bar{\phi}_j') + a_T\bar{\phi}_j' \qquad (10')$$

or, regrouping and defining

$$\Lambda_j' = \frac{\kappa_j^2 - \bar{B}_j^2}{B_g^2}$$

$$f(\bar{\phi}_j') = \left(\frac{M^2B_g^2}{\alpha_x}\right)\Lambda_j' - \frac{\alpha_T}{\alpha_x}\bar{\phi}_j' \qquad (10a')$$

These are just the equations given by Ward (*1*) extended to include the power coefficient, direct formation of Xe^{135}, and the spatial distribution of the buckling (or of the multiplication constant).

The dashed line in Fig. 2 shows the comparison between Λ_1' and Λ_1 for flattened one-dimensional piles. The values are the same for a sine shape, and the agreement is good for flux shapes which are flat over no more than 40% of a linear dimension. For flatter fluxes, Λ_1' rises above Λ_1. For completely flat piles, the error in Λ_1' becomes very large, as a result of the omission of the cross terms $\bar{B}_j^2$.

However, when one wishes to take into account flux flattening in piles where the power distribution does not differ greatly from the geometrical mode, the ease of computing κ_1^2 and $\bar{B}_1^2$ for piles of known geometry and power distribution makes Eq. 10′ attractive. Figure 2 indicates that the use of Eq. 10′ is valid if the flux is flat over no more than 40% of a linear dimension.

Oscillation Periods

At the oscillation threshold, the period is given by $2\pi/(c)^{1/2}$, where c is defined in Eq. 9. Since b is zero, c can be written as

$$c = \lambda_i\left[\lambda_x + \sigma_x\bar{\phi}_j + (\lambda_i + \lambda_x + \sigma_x\bar{\phi}_j)\left(\frac{1-\bar{x}_j}{\bar{x}_j - \gamma_x}\right)\right] \qquad (11)$$

Figure 4 shows the periods computed for the one-dimensional piles whose thresholds are shown in Fig. 3.

Approximations Used

The approximations used in computing the thresholds shown in Fig. 3 were as follows:

• $\bar{\phi}_1$ is treated as if it were the aver-

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Thermal-Neutron Data For the Elements

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The widespread acceptance of an earlier thermal-neutron-data tabulation by Kroeger (*1*) has stimulated this updated compilation. Intended primarily for calculations related to reactor studies, it should also prove useful in neutron-source and shielding studies.

The material, for the most part, is found in the references or calculated using standard techniques, such as are presented by Glasstone and Edlund (*2*). The cross sections are the 2,200-m/sec cross sections. Non-$1/v$ cross sections are corrected to yield a result equivalent to a $1/v$ cross section in a Maxwellian thermal-neutron flux.

The average value for the cosine of the scattering angle, $\bar{\mu}_0$, is calculated from $\bar{\mu}_0 = 2/3A$, where A is the mass of the scattering nucleus.

The average logarithmic energy decrement, ξ, is found from the approximation $\xi = 2/(A + \frac{2}{3})$ for the elements with mass larger than 10. For the lighter elements, $\xi = 1 + [(A-1)^2/2A][\ln (A-1)/(A+1)]$.

For the fissionable elements, for which the moderation area has little meaning, that column contains the microscopic fission cross section.

The diffusion coefficient is $D = L^2\Sigma_a$ or $D = \lambda_s/3(1-\bar{\mu}_0)$, where $\lambda_s/(1-\bar{\mu}_0)$ is the transport mean free path. The transport cross sections and mean free path were deleted to allow space for the resonance integral, the moderation area and the diffusion coefficient.

The cross sections given in the table are the absorption (a), scattering (s) and total (t) cross sections.

* * *

This work was performed under the auspices of the U. S. Atomic Energy Commission.

Atomic no.	Element or compound	Atomic or mole. wgt.	Density (gm/cm³)	Nuclei per unit vol. (x10²⁴/cm³)	$1-\mu_0$	ξ	Microscopic cross section (barns) σ_a	σ_s	σ_t	Macroscopic cross section (cm⁻¹) Σ_a	Σ_s	$*\Sigma_t$	Mean free path (cm) λ_a	λ_s	λ_t	Resonance integral (barns)	Diffusion length (cm)	Diffusion coeff. (cm)
1	H	1.008	8.9χ	5.3χ	0.3386	1.000	0.33	38	38	1.7χ	0.002	0.002	0.6/χ	525	521		1,610	518
	H_2O	18.016	1.00	0.0335*	0.676	0.948	0.66	103	103	0.022	3.45	3.45	45	0.290	0.290		2.73‡	0.164
	D_2O	20.030	1.10	0.0331*	0.884	0.570	0.001	13.6	13.6	3.3χ	0.449	0.449	0.3/χ	2.23	2.23		116 ‡	0.62
2	He	4.003	17.8χ	2.6χ	0.8334	0.425	0.007	0.8	0.807	0.02χ	2.1χ	2.1χ	50/χ	4,760	4,760		2.8/χ	0.16/χ
3	Li	6.940	0.534	0.0463	0.9047	0.268	71	1.4	72.4	3.29	0.065	3.35	0.304	15.4	0.299	28	0.605	1.17
4	Be	9.013	1.85	0.1236	0.9259	0.209	0.010	7.0	7.01	124χ	0.865	0.865	806	1.16	1.16		22 ‡	0.60
	BeO	25.02	3.025	0.0728*	0.939	0.173	0.010	6.8	6.8	73χ	0.501	0.501	1,370	2.00	2.00		32 ‡	0.75
5	B	10.82	2.45	0.1364	0.9394	0.171	755	4	759	103	0.546	104	0.010	1.83	0.010		0.112	1.28
6	C	12.011	1.60	0.0803	0.9444	0.158	0.003	4.8	4.80	25χ	0.385	0.385	3,845	2.60	2.60		54.4 ‡	0.778
7	N	14.008	0.0013	5.3χ	0.9524	0.136	1.88	10	11.9	9.9χ	50χ	60χ	0.1/χ	2,000	1,667		2,710	661
8	O	16.000	0.0014	5.3χ	0.9583	0.120	20χ	4.2	4.2	0.000	21χ	21χ	--	4,760	4,760		4.1/χ	166
9	F	19.00	0.0017	5.3χ	0.9649	0.102	0.001	3.9	3.90	0.01χ	20χ	20χ	100/χ	5,000	5,000		1.9/χ	1,729
10	Ne	20.183	0.0009	2.6χ	0.9667	0.0998	1	2.4	3.40	2.6χ	6.2χ	8.9χ	0.3/χ	0.1/χ	0.1/χ		0.12/χ	4,539
11	Na	22.991	0.971	0.0254	0.9710	0.0845	0.515	4.0	4.52	0.013	0.102	0.115	76.3	9.80	8.70	0.27	15.8	3.27
12	Mg	24.32	1.74	0.0431	0.9722	0.0811	0.063	3.6	3.66	0.003	0.155	0.158	368	6.45	6.33	0.9	28.5	2.21
13	Al	26.98	2.699	0.0602	0.9754	0.0723	0.230	1.4	1.63	0.014	0.084	0.098	72.5	11.9	10.2	0.18	29.0	5.52
14	Si	28.09	2.42	0.0622	0.9762	0.0698	0.13	1.7	1.83	0.007	0.089	0.096	147	11.3	10.6	0.5	23.7	3.81
15	P	30.975	1.82	0.0354	0.9785	0.0632	0.20	5	5.20	0.007	0.177	0.184	141	8.55	5.43	2	16.4	1.90
16	S	32.066	2.07	0.0389	0.9792	0.0612	0.49	1.1	1.59	0.019	0.043	0.062	52.4	23.3	16.2	0.6	19.5	7.24
17	Cl	35.457	0.0032	5.3χ	0.9810	0.0561	32.6	16	48.6	0.002	80χ	0.002	625	1,240	417	12	429	294
18	A	39.944	0.0018	2.6χ	0.9833	0.0492	0.62	1.5	2.12	2.6χ	3.9χ	5.5χ	0.5/χ	0.2/χ	0.2/χ		0.18/χ	0.63/χ

* Molecules/cm³ † Activation integral ‡ Measured $\chi = \times 10^5$ $/\chi = \times 10^{-5}$

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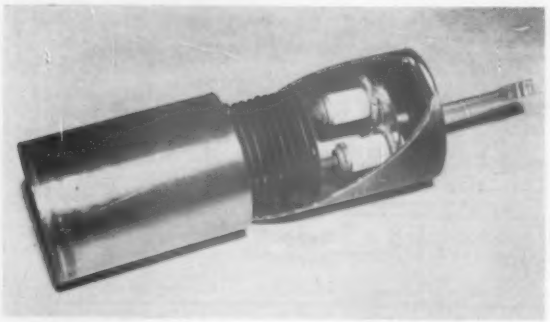
Thermal-Neutron Data For the Elements

Atomic no.	Element or compound	Atomic or mole. wgt.	Density (gm/cm³)	Nuclei per unit vol. (x10²⁴/cm³)	$1-\mu_o$	ξ	Microscopic cross section (barns)			Macroscopic cross section (cm⁻¹)			Mean free path (cm)			Resonance integral (barns)	Diffusion length (cm)	Diffusion coeff. (cm)
							σ_a	σ_s	σ_t	Σ_a	Σ_s	Σ_t	λ_a	λ_s	λ_t			
19	K	39.100	0.87	0.0134	0.9829	0.0504	1.97	1.5	3.47	0.026	0.020	0.047	37.9	49.8	21.5	1.1	22.3	13.1
20	Ca	40.08	1.55	0.0233	0.9833	0.0492	0.43	3.0	3.43	0.010	0.070	0.080	100	14.3	12.5	2	21.7	4.70
21	Sc	44.96	2.5	0.0335	0.9852	0.0438	23.5	24	47.5	0.787	0.804	1.59	1.29	1.24	0.628	10.7†	0.666	0.349
22	Ti	47.90	4.5	0.0566	0.9861	0.0411	5.8	4	9.8	0.328	0.226	0.555	3.05	4.43	1.80	3.0	1.86	1.13
23	V	50.95	5.96	0.0704	0.9869	0.0387	5.1	5	10.1	0.359	0.352	0.711	2.79	2.84	1.41	2.2†	1.48	0.786
24	Cr	52.01	7.1	0.0822	0.9872	0.0385	2.9	3.0	5.9	0.238	0.247	0.485	4.20	4.05	2.06	1.9	2.18	1.13
25	Mn	54.94	7.2	0.0789	0.9878	0.0359	13.2	2.3	15.5	1.04	0.181	1.22	0.962	5.52	0.820	10.8	0.898	0.839
26	Fe	55.85	7.86	0.0848	0.9881	0.0353	2.53	11	13.5	0.215	0.933	1.15	4.65	1.07	0.870	2.3	1.27	0.345
27	Co	58.94	8.9	0.0910	0.9887	0.0335	37.0	7	44.0	3.37	0.637	4.00	0.297	1.57	0.250	48	0.273	0.251
28	Ni	58.71	8.90	0.0913	0.9887	0.0335	4.6	17.5	22.1	0.420	1.60	2.02	2.38	0.63	0.495	4	0.688	0.199
29	Cu	63.54	8.94	0.0848	0.9896	0.0309	3.69	7.2	10.9	0.313	0.611	0.924	3.19	1.64	1.08	4	1.26	0.497
30	Zn	65.38	7.14	0.0658	0.9897	0.0304	1.06	3.6	4.66	0.070	0.237	0.307	1.43	4.22	0.326	2	4.38	1.34
31	Ga	69.72	5.91	0.0511	0.9905	0.0283	2.77	4	6.77	0.142	0.204	0.346	7.04	4.90	2.89	9.2†	3.18	1.44
32	Ge	72.60	5.36	0.0445	0.9909	0.0271	2.35	3	5.35	0.105	0.134	0.239	9.52	7.46	4.18		4.53	2.15
33	As	74.91	5.73	0.0461	0.9911	0.0264	4.1	6	10.1	0.189	0.277	0.466	5.29	3.61	2.15	33	2.37	1.06
34	Se	78.96	4.8	0.0366	0.9916	0.0251	11.8	11	22.8	0.432	0.403	0.835	2.31	2.48	1.20		1.26	0.686
35	Br	79.916	3.12	0.0235	0.9917	0.0247	6.6	6	12.6	0.155	0.141	0.296	6.45	7.09	3.38	147†	3.54	1.94
36	Kr	83.80	0.0037	2.6χ	0.9921	0.0236	28	7.2	35.2	73χ	70χ	91χ	1,400	3,300	1,100		1,180	1,010
37	Rb	85.48	1.53	0.0108	0.9922	0.0233	0.70	12	12.7	0.008	0.130	0.138	132	7.69	72.4		18.3	2.55
38	Sr	87.63	2.54	0.0175	0.9925	0.0226	1.16	10	11.2	0.020	0.175	0.195	49.3	5.71	5.13	16	9.62	1.88
39	Yt	88.92	5.51	0.0373	0.9925	0.0223	1.3	3	4.3	0.048	0.112	0.160	20.8	8.93	6.25	0.91†	7.57	2.75
40	Zr	91.22	6.4	0.0423	0.9927	0.0218	0.180	8	8.2	0.008	0.338	0.346	132	2.96	2.89	3	11.4	0.99
41	Nb	92.91	8.4	0.0545	0.9928	0.0214	1.1	5	6.1	0.060	0.272	0.333	16.7	3.70	3.00	8.3	4.43	1.18
42	Mo	95.95	10.2	0.0640	0.9931	0.0207	2.5	7	9.5	0.160	0.448	0.608	6.25	2.23	1.64	13	2.09	0.699
43	Tc	98			0.9932	0.0203	100			0.179	0.436	0.615	5.59	2.30	1.63			
44	Ru	101.1	12.2	0.0727	0.9934	0.0197	2.46	6	8.5	11.0	0.360	11.4	0.091	2.78	.088		1.99	0.709
45	Rh	102.91	12.5	0.0732	0.9935	0.0193	150	5	155	0.551	0.248	0.799	1.81	4.03	1.25	575	0.107	0.126
46	Pd	106.4	12.16	0.0689	0.9937	0.0187	8	3.6	11.6	3.63	0.352	3.98	0.275	2.84	0.251	23	1.30	0.931
47	Ag	107.88	10.5	0.0586	0.9938	0.0184	62	6	68	154	0.325	154	0.007	3.08	0.007	600	0.290	0.305
48	Cd	112.41	8.65	0.0464	0.9940	0.0178	3,315	7	3,322	7.26	0.084	7.34	0.138	11.9	0.136	2,570†	0.0083	0.011
49	In	114.82	7.28	0.0382	0.9942	0.0173	190	2.2	192	0.020	0.132	0.152	50.0	7.58	6.58	4.3	0.171	0.212
50	Sn	118.70	6.5	0.0330	0.9944	0.0167	0.6	4	4.6	0.182	0.142	0.324	5.49	7.04	3.09	115	11.0	2.42
51	Sb	121.76	6.69	0.0331	0.9945	0.0163	5.5	4.3	9.8	0.133	0.148	0.281	7.52	6.76	3.56	36	3.21	1.87
52	Te	127.61	6.24	0.0295	0.9948	0.0155	4.5	5	9.5	0.157	0.084	0.241	6.37	11.9	4.15	130	3.79	1.91
53	I	126.91	4.93	0.0234	0.9948	0.0157	6.7	3.6	10.3	0.001		0.001	1,053	9,091	909	1,012	4.29	2.89
54	Xe	131.30	0.0059	2.7χ	0.9949	0.0152	35	4.3	39.3	0.001		0.001	1,053	9,091	909	1,012	4.29	2.89
55	Cs	132.91	1.873	0.0085	0.9950	0.0150	29	20	49	0.246	0.170	0.416	4.07	5.88	2.40		2.49	1.52
56	Ba	137.36	3.5	0.0154	0.9951	0.0145	1.17	8	9.2	0.018	0.123	0.141	55.6	8.13	7.09	7.5	12.1	2.64
57	La	138.92	6.19	0.0268	0.9952	0.0143	8.9	15	24	0.239	0.403	0.642	4.18	2.47	1.57	11	1.77	0.746
58	Ce	140.13	6.78	0.0292	0.9952	0.0142	0.7	9	9.7	0.021	0.262	0.283	4.89	3.82	3.53		7.82	1.25
59	Pr	140.92	6.78	0.0290	0.9953	0.0141	11.2	4	15.2	0.324	0.116	0.440	3.08	8.62	2.27	7	2.38	1.84

60	Nd	144.27	6.95	0.0290	0.9954	0.0138	46	16	62	1.33	0.464	1.79	0.752	2.16	0.559	40	0.586	0.457	60
61	Pm	145			0.9954	0.0137	60												61
62	Sm	150.35	7.7	0.0309	0.9956	0.0133	8,250	5	8,255	255	0.155	255	0.004	6.45	0.004	1,750†	0.005	0.006	62
	Sm_2O_3	348.70	7.43	0.0128*	0.974	0.076	16,500	22.6	16,500	211	0.289	211	0.005	3.46	0.005				
63	Eu	152.0	5.22	0.0207	0.9956	0.0131	4,370	8	4,378	90.5	0.166	90.6	0.011	6.02	0.011	950†	0.0138	0.0172	63
	Eu_2O_3	352.00	7.42	0.0127*	0.978	0.063	8,740	30.2	8,770	111	0.383	111	0.009	2.61	0.009				
64	Gd	157.26	7.95	0.0305	0.9958	0.0127	3,900			1,190			0.001						64
65	Tb	158.93	8.33	0.0316	0.9958	0.0125	44			1.39			0.725						65
66	Dy	162.51	8.56	0.0317	0.9959	0.0122	1,100	100	1,200	34.9	3.17	38.1	0.029	0.315	0.026		0.096	0.323	66
	Dy_2O_3	372.92	7.81	0.0126*	0.993	0.019	2,200	214	2,414	27.7	2.7	30.4	0.036	0.37	0.033				
67	Ho	164.94	8.76	0.0320	0.9960	0.0121	64			2.05			0.489						67
68	Er	167.27	9.16	0.0330	0.9960	0.0119	166	15	181	5.44	0.495	5.98	0.182	2.02	0.167		0.194	0.207	68
69	Tm	168.94	9.35	0.0333	0.9961	0.0118	118			3.93			0.255						69
70	Yb	173.04	7.01	0.0244	0.9961	0.0115	36	12	48	0.878	0.293	1.17	1.14	3.41	0.852		0.899	0.710	70
71	Lu	174.99	9.74	0.0335	0.9962	0.0114	108			3.62			0.278			720			71
72	Hf	178.5	13.3	0.0449	0.9963	0.0112	105	8	113	4.71	0.359	5.07	0.212	2.79	0.197	2,800	0.232	0.253	72
73	Ta	180.95	16.6	0.0553	0.9963	0.0110	21.3	5	26.3	1.18	0.277	1.46	0.847	3.61	0.685	590†	0.738	0.643	73
74	W	183.86	19.3	0.0632	0.9964	0.0108	19.2	5	24.2	1.21	0.316	1.53	0.826	3.16	0.654	170	0.698	0.590	74
75	Re	186.22	20.53	0.0664	0.9964	0.0107	84	14	98	5.58	0.930	6.51	0.180	1.08	0.015	620†	0.170	0.162	75
76	Os	190.2	22.48	0.0712	0.9965	0.0105	14.7	11	25.7	1.05	0.783	1.83	0.952	1.28	0.546		0.556	0.336	76
77	Ir	192.2	22.42	0.0703	0.9965	0.0104	430			30.2				.033		2,190†			77
78	Pt	195.09	21.37	0.0660	0.9966	0.0102	8.1	10	18.1	0.535	0.660	1.19	1.87	1.52	0.840	69	0.905	0.438	78
79	Au	197	19.32	0.0591	0.9966	0.0101	98	9.3	107.3	5.79	0.550	6.34	0.173	1.82	0.158	1,558†	0.183	0.194	79
80	Hg	200.61	13.55	0.0407	0.9967	0.0099	360	20	380	14.7	0.814	15.5	0.068	1.23	0.065	73	0.077	0.088	80
81	Tl	204.39	11.85	0.0349	0.9967	0.0098	3.3	14	17.3	0.115	0.489	0.604	8.70	2.04	1.66	38†	2.38	0.651	81
82	Pb	207.21	11.35	0.0330	0.9968	0.0096	0.170	11	11.2	0.006	0.363	0.369	179	2.75	2.71	0.1	12.8	0.918	82
83	Bi	209.00	9.747	0.0281	0.9968	0.0095	0.032	9.4	9.4	0.001	0.264	0.265	909	3.79	3.77	0.5	32.0	1.126	83
84	Po	210	9.24	0.0265	0.9968	0.0095													84
85	At	211			0.9968	0.0094													85
86	Rn	222	0.0097	2.6_X	0.9970	0.0090	0.7												86
87	Fr	223			0.9980	0.0089													87
88	Ra	226.05	5	0.0133	0.9971	0.0088	20			0.266			3.76						88
89	Ac	227			0.9971	0.0088	510												89
90	Th	232.05	11.3	0.0293	0.9971	0.0086	7	12.5	19.5	0.205	0.366	0.571	4.88	2.73	1.75	69.8†	2.7	1.49	90
91	Pa	231	15.4	0.0402	0.9971	0.0086	260			10.4			0.096						91
92	U	238.07	18.9	0.04783	0.9972	0.0084	7.6	8.3	15.9	0.364	0.397	0.761	2.75	2.52	1.31	290†	1.37	0.683	92
	UO_2	270.07	10	0.0223*	0.9776	0.036	7.6	16.7	24.3	0.169	0.372	0.542	5.92	2.70	1.85		1.897	0.615	
93	Np	237			0.9972	0.0084	170												93
94	Pu	239	19.74	0.0498	0.9972	0.0083	1,145	9.6	1,155	57.0	0.478	57.5	0.018	2.09	0.012	250	0.0708	0.286	94
95	Am	242			0.9973	0.0082	8,000												95
96	Cm	245			0.9973	0.0081													96
97	Bk	249			0.9973	0.0081	500												97
98	Cf	249			0.9973	0.0079	900												98
99	E	253			0.9974	0.0079	160												99
100	Fm	256			0.9974	0.0078													100
101	Mv	260			0.9974	0.0077													101

* Molecules/cm³ † Activation integral ‡ Measured $_x$ = $\times 10^5$ $/_x$ = $\times 10^{-5}$



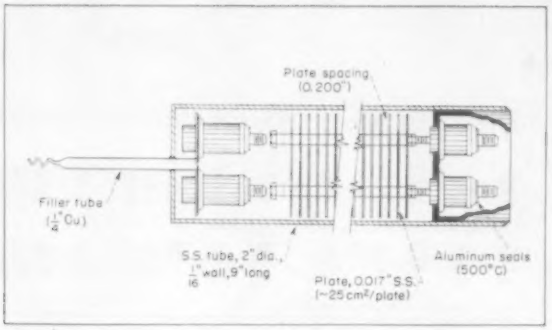


FIG. 1. Test model of fission chamber for high-temperature neutron detection

Neutron Detectors For Operation at 400° C

By STEFAN G. KAUFMANN and LEROY E. PAHIS
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The instrumentation needs of the contemplated second Experimental Breeder Reactor (EBR-II) point up the advantages to be gained with nuclear detectors that can operate at elevated temperatures.

The reactor core is designed to operate submerged in a large sodium bath at about 400° C. The instrument thimbles must reach into regions near the core for sufficient flux to provide an adequate signal during startup and low-power operations. Thus the thimbles will be at the sodium temperature.

Two approaches can be used under these conditions: the nuclear detectors can be designed to operate at the sodium-bath temperature, or, as a more conservative approach, the instrument thimbles can incorporate cooling ducts and temperature-monitoring instruments to accommodate conventional detectors. Until high-temperature instruments are shown to be reliable for extended periods of service, the conservative approach will be used. Although this is the working attitude at the present time, a development program for high-temperature instruments has been encouraged. Results of such work are reported here.

The philosophy of our work has been to study only those detectors that work on the simple mechanism of ion production and collection, i.e., ion chambers and ion counters. The entire range of reactor power level can be monitored by these detectors. There is thus no immediate necessity to cope with the more difficult problems associated with signal amplification, i.e., proportional counters.

The construction of either detector type is simple (Fig. 1). The body is prepared from commercially available stainless-steel tubing. The pulse chamber has a single high-voltage connector at one end with a grounded metal housing, whereas the current chamber has two such connectors so that the chamber body can be connected to an independent ground. The hermetic insulators are commercial alumina-to-metal seals welded into the stainless-steel bodies by the Heliarc process, which does not offend the insulating properties or the vacuum tightness of the seals.

Neutron-sensitive plates are stacked parallel to the flat end plates of the cylindrical counter bodies. These plates are punched from 0.017-in. stainless sheet and sensitized through the deposition of an evaporated uranium film of about ¼ mg/cm². Though this is not the maximum permissible thickness for fission detectors, it has been chosen so that the pulse-height distribution is clearly visible in the pulse counter.

Changes in the plateau characteristics are expected to be the most sensitive indication of temperature aging of the counter. The counters are filled with three atmospheres of argon gas at room temperature and sealed by hard-soldering the copper filling tube. No soldering flux is permitted on exposed surfaces inside the counters since flux has previously been suspected as the cause of counter failure.

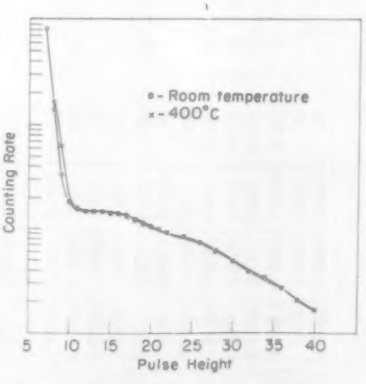
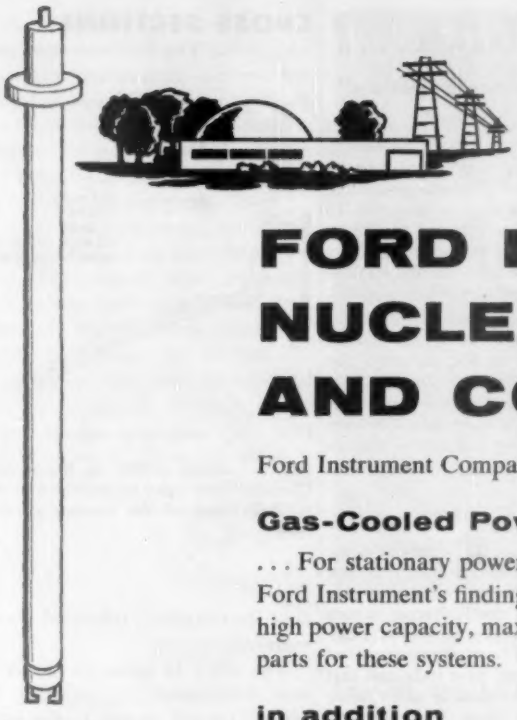


FIG. 2. Comparison of counter characteristics at room and high temperatures

Figure 2 compares fission-counter performance at room temperature and at 400° C. It is apparent that the pulse-height distribution is not influenced by the temperature difference. The voltage-dependence curve shows



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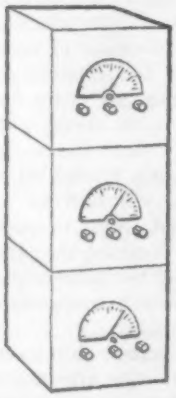

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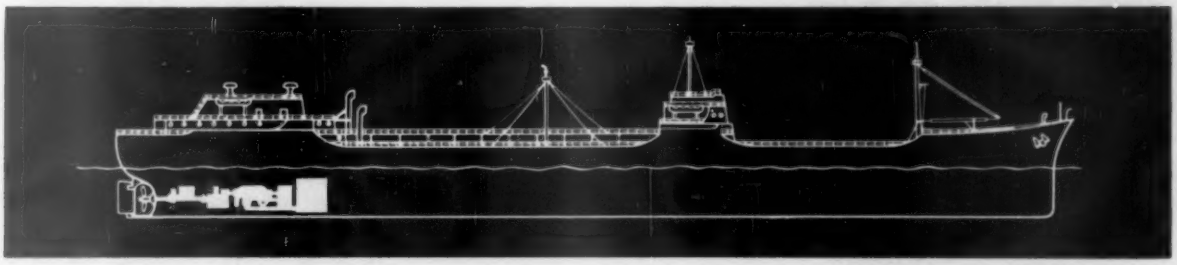

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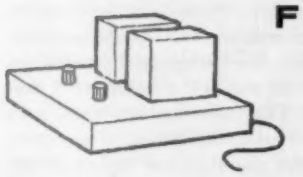

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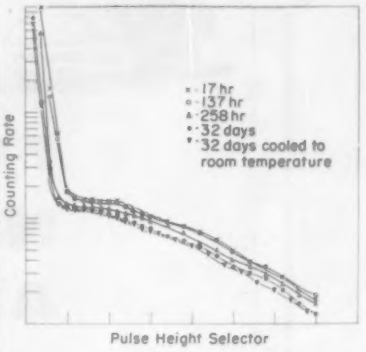

FIG. 3. Aging effects on fission counter. Chambers are aged by exposure at 400° C to PoBe neutrons for various periods of time

that the counter is saturated above 50 volts.

The effect of aging on the counter was determined by exposing it at 400° C for one month to the neutron flux of a PoBe source. The plateaus of Fig. 3 show a decrease in noise pulse size with age and approximate constancy of counting rate in the flat region. Since the source decays with a 138-day half-life, a slight decrease in signal is expected. For the last set of points, the counter was aged for 32 days at 400° C and cooled to room temperature before obtaining the data. It is apparent that the pulse-height distribution maintained its temperature independence after aging.

The background-current data given in Fig. 4 was obtained by operating a two-connector detector as an ion chamber supplying direct current. The current was measured with an RCA microammeter with full-scale voltage drop of 0.5 volt on all scales.

At room temperature a background current of $\sim 1.5 \times 10^{-9}$ amperes is evident. This number is in agreement with the expected signal from the alpha activity of the sensitizing uranium film on the chamber plates. Upon reversing the applied voltage, the current reverses but does not reproduce the original reading.

This asymmetry is ascribed to a possible zero error in the sensitive micromicroammeter. As the temperature rises, the background current decreases to somewhat below 10^{-9} amperes. This value has been found to be constant over the period of a month when the chamber was tested at un-

interrupted high temperature in a weak beam from the CP-5 reactor. Although the background current was temperature sensitive, the signal obtained when the thermal-neutron beam was turned on was nearly independent of the temperature and remained constant over the testing period.

A second chamber, coated with boron instead of uranium so that no alpha-current background was expected, yielded a similar stray background current of 10^{-9} amperes when the chamber was taken up to 400° C. The suspicion that this background might be developed through strain voltages in the alumina seals was dispelled through a test in which a seal, Heliarced into a stainless-steel chamber bottom, was heated and

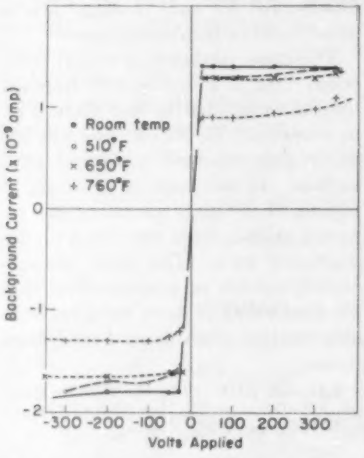

FIG. 4. Background current of neutron detector as function of temperature and voltage

tested with negative results for stray voltages and currents.

The absolute sensitivity of the test chambers has not been established, though the estimate is 10^{-14} amp/nv.

In tests of the counter with a commercial A61B amplifier, observed pulse heights were 20 mv, max. Deadtime has not been observed on the fission counters because the fission pulse is localized and very fast and does not paralyze the rest of the counter. We have not tried the ion chamber described here at high fluxes, though a comparable chamber filled with BF_3 has permitted us to draw currents in the microampere range and was saturated for such currents at about 100 volts.

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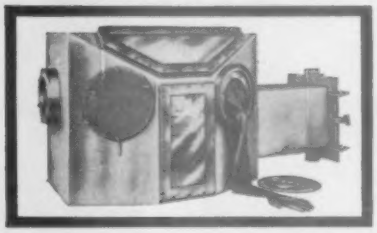

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Organic-Glass Scintillators

By JOHN W. DOWNS and FORREST L. SMITH
Aeronautical Research Laboratory, Wright Air Development Center
Wright-Patterson Air Force Base, Ohio

As a contribution to the development of new scintillators, a study has been made of two organic silane compounds, triphenyl-*p*-biphenylylsilane and phenyltri-*p*-biphenylylsilane.* These compounds are of interest because they are natural glass formers as well as good scintillators.

When prepared from pure materials, these glass scintillators are transparent, of good optical quality and easy to mold in various sizes and shapes. Their efficiency relative to a single crystal of anthracene when exposed to gamma radiation is about 60%. In addition, they are readily soluble in xylene, toluene, benzene and other organic solvents to form clear liquid scintillators.

Glass scintillators have some of the desirable characteristics of both solid and liquid scintillators. They are crystal-like in appearance and may be used much in the same way that single crystals of anthracene are now used. They approach the versatility of liquid scintillators in that counting samples or other foreign substances such as wave shifters can be incorporated.

Also, they may be molded to any desired shape or drawn out to a fine scintillating fiber. They may be poured at low temperature directly onto the face of a photomultiplier tube, thus providing a direct tube-to-scintillator coupling.

Physical Properties

The compounds are white crystalline powders. Triphenyl-*p*-biphenylylsilane has a melting point of 159° C and a maximum solubility of 175 gm/liter in benzene. Phenyltri-*p*-biphenylylsilane has a melting point of 155° C and solubility of 228 gm/liter in benzene.*

Highly pure material is required to make a transparent glass with good transmission qualities. Purification was achieved by dissolving the compounds in benzene, passing the solution through a column containing Florisil† in heptane, followed by a series of four-to-six recrystallizations from a benzene-heptane mixture.

Preparation of Specimens

Glass specimens were prepared simply by melting a portion of silane in a beaker (120° C), cooling to approximately 70° C and pouring into a nickel mold of the desired size.

The mold consisted of nickel sheet rolled into a cylinder and fastened around a small Lucite base about 2 in. in diameter. The Lucite base was left on the glass to provide a polished lower surface. In this way, no polishing or cutting of the glass specimens was required prior to their use with a photomultiplier tube. The silane glass is slightly soluble in mineral oil so that the Lucite disk protects the glass from deterioration when mineral oil is used

* The silane compounds were synthesized by the Chemistry Research Branch, Aeronautical Research Laboratory, Wright Air Development Center. They were prepared by a modified "Wurtz" reaction in which chlorosilane and chlorobenzene are condensed with sodium in ether. The product is isolated by evaporation to dryness and extracted with benzene [L. Spialter, D. Priest, C. W. Harris, *J. Am. Chem. Soc.* **77**, 6227 (1955).]

† Florisil, produced by the Floridin Company, Tallahassee, Fla., contains 15% MgO, 84% SiO_2, and 0.5% Na_2SO_4.

Decay Times of Common Scintillators

Scintillator	*Type*	*Decay time (sec)*
Anthracene	Organic crystal	3.5×10^{-8}*
Stilbene	Organic crystal	6×10^{-9}*
P-terphenyl in xylene	Organic liquid	5×10^{-9}†
Polyvinyl-toluene +4% *p*-terphenyl +0.1% diphenylstilbene	Plastic	4×10^{-9}*
NaI(Tl)	Inorganic crystal	2.5×10^{-7}†
Silane glass	Organic glass	2×10^{-8}

* R. Swank, W. Buck, *Rev. Sci. Instr.* **26**, 15 (1955).

† J. B. Birks, "Scintillation Counters," pp. 45 and 52 (McGraw-Hill Book Co., New York, 1953).

as a coupling agent. Lucite is an efficient light pipe so that no appreciable loss in efficiency occurs by its use.

Method of Evaluation

The efficiency of the glass scintillators was measured relative to a 1-in.-thick anthracene crystal. Relative pulse height was used as a measure of efficiency. The scintillator was coupled to a DuMont 6292 photomultiplier. The photomultiplier output was amplified by an Atomic Instrument Co. model 205-B linear amplifier, and the amplified pulse was fed into a Tektronix type 517A oscilloscope. Pulse height was read directly from the oscilloscope. Pulse height as well as counting rate were checked by feeding the discriminator-output pulse of the amplifier into a scaler.

Pulse decay time was measured by feeding the pulse from the photomultiplier tube directly into the fast oscilloscope.

A pulse-height analysis of Cs^{137} gamma rays was made using a single-channel pulse-height analyzer.

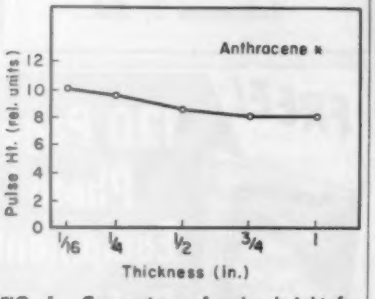

FIG. 1. Comparison of pulse height for various thicknesses of silane glass. Measurement of anthracene crystal is shown

Relative Efficiency

Glass samples ranging in thickness from $\frac{1}{16}$ in. to 1 in. were examined for pulse height using the previously described method. The pulse height decreased with increase in thickness from ten units for the $\frac{1}{16}$-in. glass to eight units for the 1 in.

A plot of pulse height versus scintillator thickness is shown in Fig. 1. With pulse height as a measure of relative efficiency, the silane glass varies with increase in size from about 75% to 60% of the efficiency of anthracene. The decrease in pulse height with size indicates a degree of self-quenching because of either impurities or light trapping within the glass itself. This deficiency can, perhaps, be

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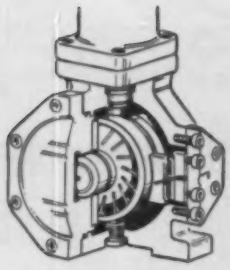

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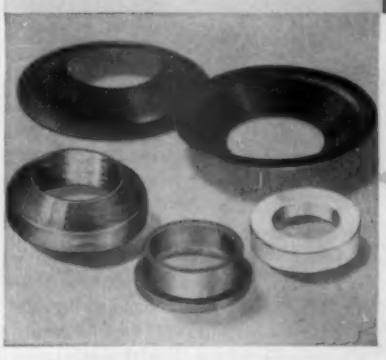

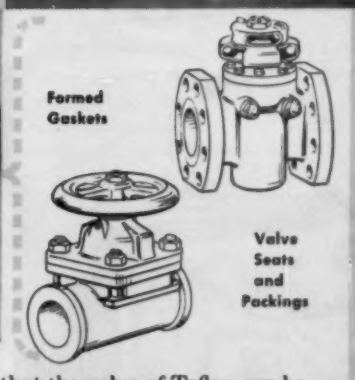

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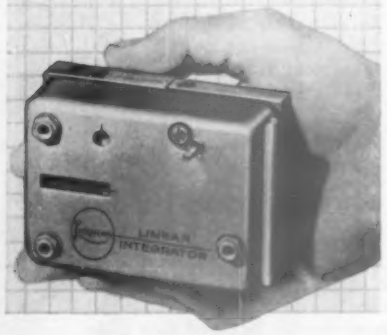

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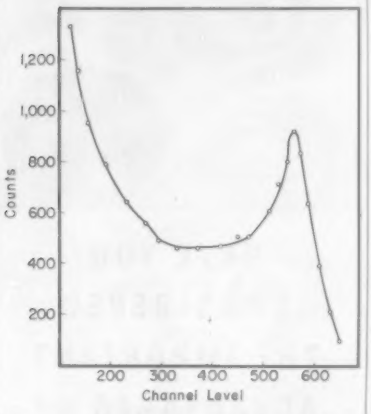

FIG. 2. Pulse height analysis of Cs^{137} gamma rays with silane-glass scintillator

overcome by increased purification.

A pulse-height analysis of Cs^{137} gamma rays using a ¾-in. silane-glass scintillator is shown in Fig. 2. The peak in Fig. 2 is a Compton edge. Because of its relatively small size and since only low-"Z" elements are present in the scintillator, it is rather improbable that an appreciable photoelectric effect occurs even with the low-energy gamma (0.6 Mev) from Cs^{137}. If a backscatter peak is present, it is most likely masked by the Compton distribution. In this regard it compares very well with anthracene and other small organic scintillators but cannot compare or compete with NaI-(Tl) for use in gamma spectroscopy.

From oscilloscope measurements, the decay time appears to be about 2×10^{-8} sec.

Spectral Characteristics

The emission spectrum of a silane glass excited by ultraviolet light was examined visually with a table spectrometer. No specific emission bands were observable. Emission appeared to occur throughout the entire visible region, i.e., red through violet. Addition of diphenylhexatrene as a wave shifter cut off the violet portion.

Absorption measurements were made using a Beckman spectrophotometer. No specific absorption bands were observed between 3,000 and 9,000 angstroms.

* * *

The author wishes to express appreciation to Dr. L. Spialter and the Chemistry Research Branch of the Aeronautical Research Laboratory, Wright Air Development Center, for providing the silane compounds used.

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Gamma-Dose Enhancement From Neutron Capture in Cd

By D. E. KLINE* and F. J. REMICK
Pennsylvania State University, University Park, Pa.

In many reactor experiments, such as studies of the effects of radiation on materials, it is desirable to reduce the intensity of the thermal neutrons entering the material to isolate the effects of various components of the radiation. This is especially true if the radiation is used primarily to study changes in the internal structure of high polymers (*1*) and other materials.

One means of eliminating the thermal neutrons is to wrap a thin shield of natural cadmium about the specimen to be irradiated. When this is done, however, the Cd(n,γ) reaction results in an additional gamma-dose rate within the specimen that supplements the dose rate present before applying the cadmium. If the material being studied is sensitive to gamma radiation, it is necessary to know to what extent the dose rate has been enhanced.

One way of doing this would be to calculate the enhancement using the energies and respective intensities of the capture gammas, together with the absorption coefficients of these different gammas in air, and then numerically integrate the effect of all the gammas to find the gamma dose per thermal neutron absorbed. There are two main objections to this method, however. The first objection is that it relies too heavily on the combined capture-gamma data of various other experimenters. The use of natural cadmium as a thermal-neutron absorber in reactor experiments is well known. The gamma rays given off in the (n,γ) reaction have been classified as capture gammas, given off almost immediately ($\sim 10^{-14}$ sec), and decay gammas (*2*). It has been found that most of the absorption occurs in Cd^{113}, present to 12.3%, which has a cross section of >20,000 barns, and that the total decay-gamma contribution of all the other isotopes present is small compared to the capture-gamma contribution of Cd^{113}. In addition, much work has been done in determining the energies and intensities of the gamma-ray lines of the Cd^{114} spectrum (*3*). However, in spite of all this, the data are still both incomplete and inconsistent. The second objection has to do with the fact that, to determine the dose rate, one must obtain the thermal-neutron flux corrected for the depression due to the insertion of cadmium.

FIG. 1. Portable thermal column of Penn State reactor set against core

Another method of determining enhancement would be to make actual measurements in the reactor, first with no Cd present, and then with a Cd-covered container placed in the same position. The difference obtained would be a measure of the effect of the Cd(n,γ) reaction.

Experimental Procedure

To determine the effect of the Cd(n,γ) reaction it is convenient to perform the experiment in a region where the radiation is composed mostly of thermal neutrons and gamma rays, for, as will be shown later, the gamma rays provide a means for absolute calibration of the gamma-dose rate. Except for a small percentage of epithermal neutrons, such a region is

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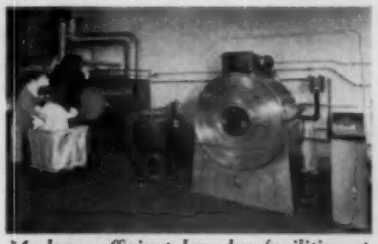

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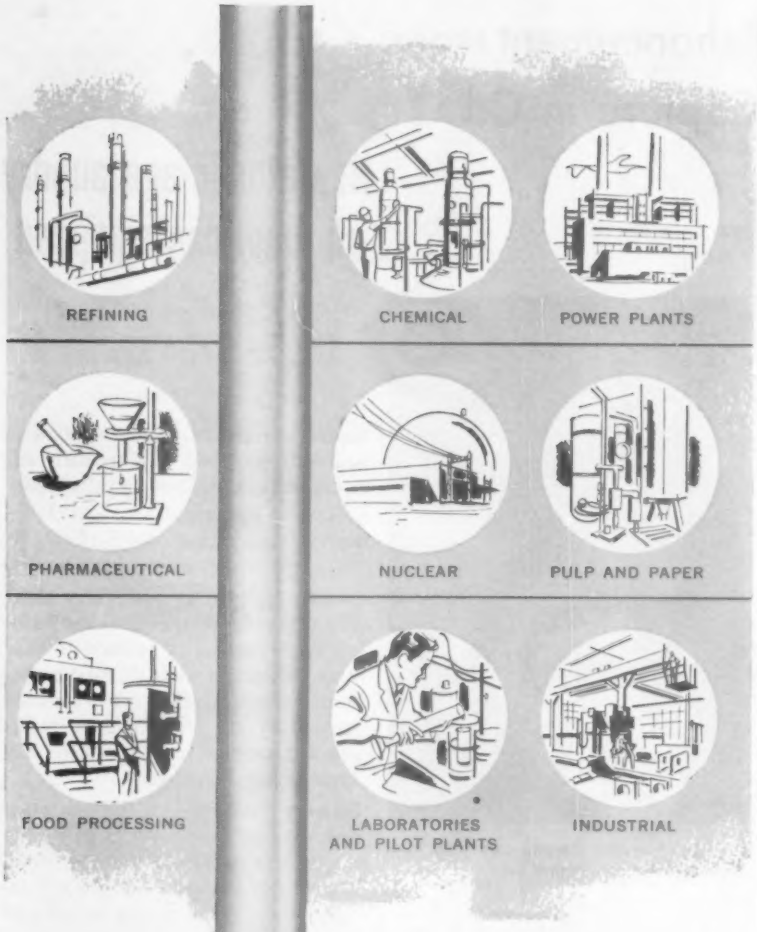

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present behind the thermal column of the Pennsylvania State University's pool-type reactor.

Most pool-type reactors have a thermal column built into an end wall with the experimental face out of the water. The portable column (Fig. 1) of this reactor is against the core (i.e., under water) with a layer of lead in between to reduce the reactor gamma-ray

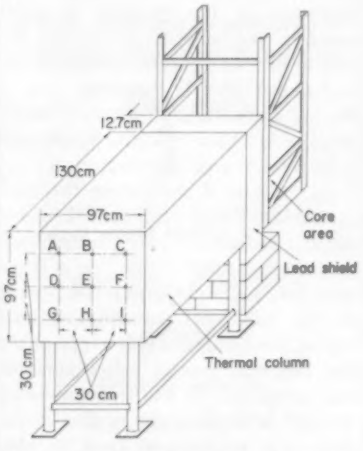

FIG. 2. Thermal column of Penn State research reactor. Experimental positions are indicated by letters *A* through *I*

intensity. The thermal column consists of an aluminum shell filled with graphite bars for moderating the fast neutrons.

As a first step in the determination of gamma-dose-rate enhancement, a study of the neutron flux and gamma-dose rates at the experimental face of the column was carried out. Measurements were made as a function of distance from the thermal column at the nine positions illustrated in Fig. 2. The thermal flux was measured by exposing gold foils at 5-cm intervals away from the column and determining the subsequent activity by counting them in a 2π flow counter. The counter and flux-measuring system was standardized with the ORNL standard graphite pile at Oak Ridge (*4*). In Fig. 3, the thermal-neutron flux, as measured along position *E* (see Fig. 2), is plotted as a function of distance from the thermal column. This plot illustrates how the cadmium ratio varies in the region. (Reactor power was 100 kw for all measurements.)

Determination of the gamma-dose-rate enhancement was carried out by

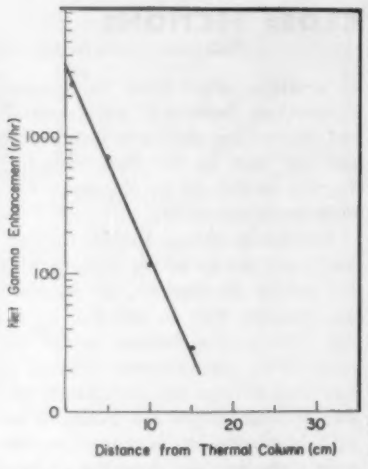

FIG. 3. Thermal-neutron flux for position *E* of thermal-column experimental face

using a Victoreen condenser R-meter placed in a watertight polyethylene tube 0.24 cm thick, 23 cm long and 2.55 cm in diameter. The outside cylindrical surface was covered with a Cd shield 0.055 cm thick. The fraction of the slow neutrons that penetrated the cadmium was less than about 5×10^{-4}. The ends were not covered because it was found that this had little effect on the results. After charging the condenser R-meter, the tube assembly was attached to the instrument bridge and placed at a point along position *E* of the thermal column for a specific period of time. When the assembly was withdrawn the condenser R-meter was read to determine the gamma-dose rate within the cadmium.

Gamma-dose rates without cadmium were measured as a function of distance

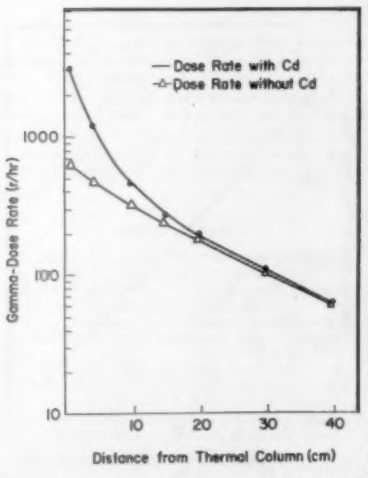

FIG. 4. Gamma-dose rates at position *E* with and without Cd

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at positions away from the thermal column face (position E) using a standard 50-cm³ ion chamber, identical to the one used at the Bulk Shielding Facility at Oak Ridge (*5*), and a low-drift electrometer (*6*).

The results obtained inside the cadmium are plotted in Fig. 4 along with the results obtained by the standard ion chamber with no cadmium covering. The curves converge as the distance from the thermal column is increased because the thermal-neutron flux responsible for the gamma-dose-rate enhancement falls off more rapidly with distance than does the original gamma-dose rate. A disagreement between the dose rate as measured by the standard ion chamber and that as measured by the condenser R-meter would result in the curves not joining but simply becoming parallel as the distance from the thermal column was increased.

Discussion of Results

The data obtained illustrate how the gamma-dose-rate enhancement depends on the rate of thermal-neutron absorption in cadmium. This enhancement, obtained by subtracting the two curves of Fig. 4, is plotted as a function of distance in Fig. 5. Because the subtraction leads to a reduction in accuracy, which becomes more serious as the difference decreases, the enhancement is plotted only over the distance where the difference is reasonably large. The relaxation length of the net enhancement curve is about 2.9 cm, which compares well with the

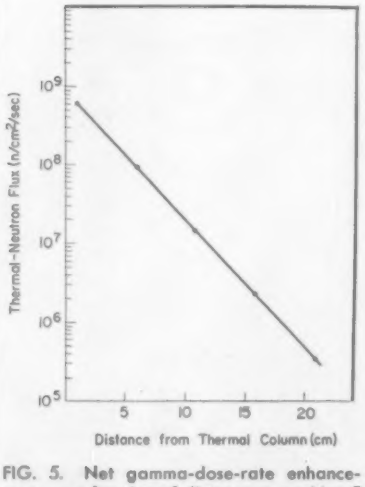

FIG. 5. Net gamma-dose-rate enhancement as a function of distance at position E

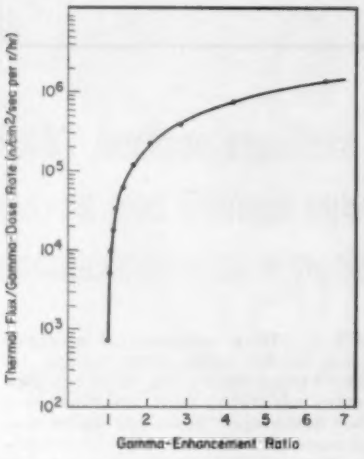

FIG. 6. Variation of enhancement ratio with increasing ratio of thermal flux to gamma-dose rate

value of 2.7 cm (about 7% difference) for the relaxation length of the thermal-neutron spectrum for position E as determined from Fig. 3. One would expect the two values to be comparable since the net gamma-dose-rate enhancement is proportional to the thermal-neutron flux.

By using Figs. 3 and 4, one can determine the gamma-dose-rate enhancement for a given thermal-neutron flux. The enhancement ratio, defined here as the ratio of the dose rate inside the Cd container to the dose rate with no cadmium present, is plotted in Fig. 6 as a function of the ratio of the neutron flux to gamma-dose rate. Results indicate that the enhancement ratio is as high as 7 for regions near the experimental face of the thermal column where the ratio of neutron flux to gamma dose is relatively high.

* * *

The authors wish to express their sincere gratitude to members of the Pennsylvania State University research reactor staff for their able and willing assistance in performing these experiments. Additional acknowledgment is due R. G. Cochran, Acting Director of the Facility, and E. S. Kenney, University health physicist, for their helpful suggestions and aid.

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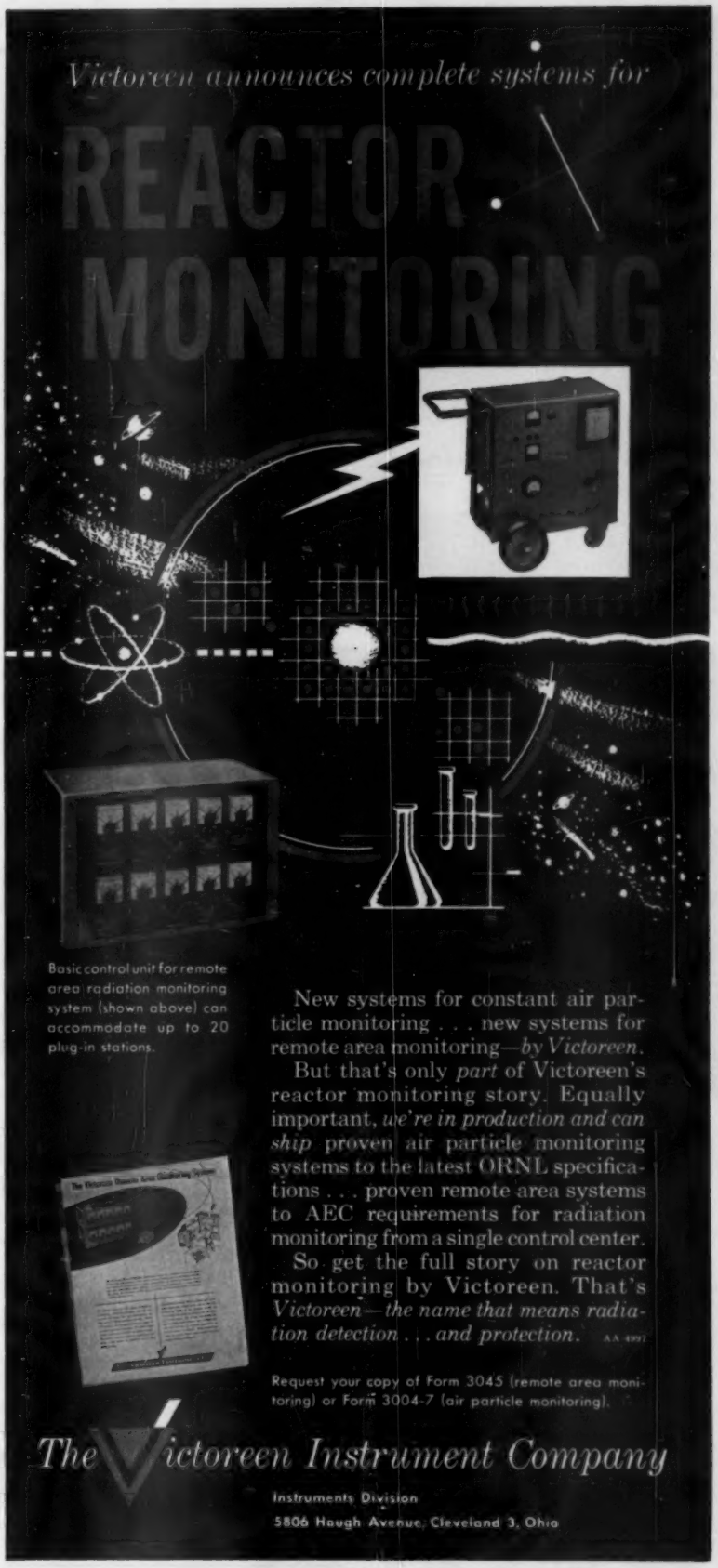
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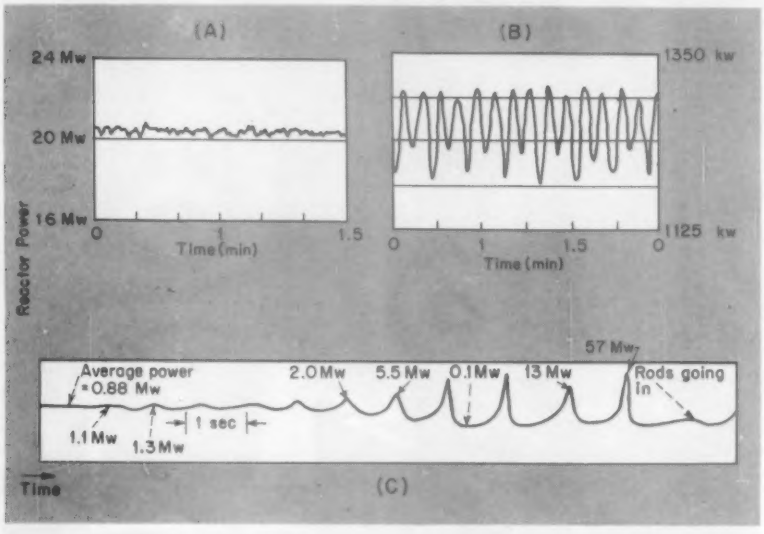

FIG. 1. Three categories of operation observed for boiling water reactors: (a) EBWR power trace during stable operation shows only boiling noise. (b) Pronounced but nondivergent oscillations during low-pressure operation in EBWR. (c) Unstable oscillations in Borax-II triggered by slight pressure change

Boiling-Water-Reactor Instability

By JOSEPH A. THIE
Argonne National Laboratory
Lemont, Illinois

A number of natural circulation boiling reactors, so far, have shown oscillatory behavior under a variety of conditions. Theoretical understanding of the phenomena currently is inadequate. However, enough evidence is now available to assist designers of similar reactors in avoiding these instabilities. In the future, rod-oscillation experiments plus a more detailed instrumentation of oscillating reactor cores should provide more theoretical information and should prove useful in determining the stability characteristics of boiling water reactors yet to be built.

Observed Behavior

Five ANL boiling reactors have been operated to date: Borax I (*1*, *2*), II (*3*), III (*3*), IV (*4*) and the Experimental Boiling Water Reactor (*5*, *6*). The instabilities of Spert I (*7*) and Borax III will not be discussed because of the similarity of these reactors to Borax I and II respectively. All the reactors are of the natural circulation, light water, single cycle boiling variety.

The fission power, as a function of time, can, in all cases, be described as falling into one of three categories: 1) stable operation in which the "boiling noise" (i.e., random power fluctuations about the mean) is greater than any single frequency, but much less than the d-c component of the power; 2) small power oscillations with an amplitude that exceeds the noise but is less than the d-c component of the power; 3) unstable oscillatory behavior having an amplitude in excess of the d-c power. All the reactors mentioned have exhibited all three characteristics, except Borax III and EBWR which were not permitted to exhibit the third. Figure 1 shows examples of these types of behavior. The third category is sometimes referred to as "divergent oscillations," since generally the reactor was scrammed while the amplitudes were increasing. However, the non-linearities and losses that limit the amplitudes of the second type would also ultimately prevent the third type from truly diverging.

Amplitude. When the reactors are

Summary of Instability Data for ANL Boiling Reactors

	Borax				
	I	*II*	*III*	*IV*	*EBWR*
Fuel	Al + U^{235}	Al + U^{235}	Al + U^{235}	ThO_2 + U^{235}	1.44% U
Configuration	plates	plates	plates	rods	plates
Thickness (in.)	0.060	0.060	0.060	0.23	0.214 & 0.279
Maximum pressure (psi)	130	300	300	300	600
Metal volume / Water volume	0.63	0.43	0.39	0.52	0.56
Resonant frequency (cps)	1.25	1.0–3.3		0.495	0.05, 0.09, 0.15 & 0.28
Small oscillation threshold	(0 psi)	(150 psi)		(0 psi)	(0 psi)
(% reactivity in voids)	<1.4	1.2 ± 0.4		0.4	<0.4
(kw/litre of core)	<6.14	7.9 ± 2.6		8.41	0.586
		(300 psi)		(300 psi)	(600 psi)
		3.2		>5.5	>2.2
		21.0		>38.35	>12.1

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(1) Figures represent minimum yield strengths required by ASME Unfired Pressure Vessel Code, Section VIII, and have been calculated as follows:

$$YS = \frac{\text{allowable stress}}{62.5\%}$$

(2) Figures taken from tests of actual heats of material manufactured by Cooper Alloy for the AEC's SPERT III program at Idaho Falls, Idaho (see Nucleonics, Aug. '57).

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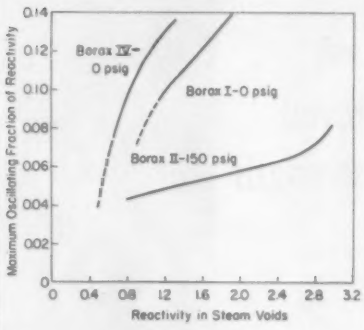

FIG. 2. Relation of reactivity oscillation amplitude to total reactivity in steam voids for Borax reactors

in the oscillatory condition, it is invariably true that, with other things constant, the average amplitude of power oscillation increases with increasing mean power. Corresponding to the oscillation in power, there is an oscillation in the amount of reactivity tied up in steam voids. The fact that the amplitude of the power oscillations increases with power means that the fraction of the steam bubble population that is oscillating also increases with power. This is shown in Fig. 2. The abscissa of this figure is obtained from the difference in control rod positions at power and at essentially zero power, calibrated in terms of the latter condition. The ordinate is obtained by dividing the oscillating reactivity,

$$\frac{\text{Oscillatory Power Amplitude} \div \text{Mean Power}}{\text{Zero Power Reactor Transfer Function}}$$

by the total reactivity in voids. The reactor transfer function (*8*) is simply the ratio one obtains from the neutron kinetics equations between the fraction of the power that oscillates and the reactivity oscillation amplitude causing it.

Frequency. The table and Fig. 3 show a variety of frequencies to be possible. The lower frequencies obtained in the reactors of larger size and/or larger fuel-element time constant are to be expected. Higher frequencies occurring at higher powers is qualitatively in agreement with the theory below. Only EBWR displayed a high harmonic content in small oscillatory operation.

Temperature. As the power oscillates the fuel temperatures are expected to oscillate. The temperature transfer

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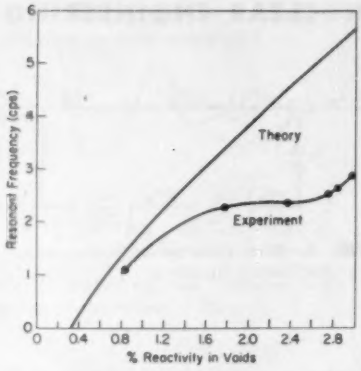

FIG. 3. Oscillation frequency vs % reactivity in voids for Borax-II

functions for typical oscillations of the different reactors show that in all cases the temperature lags behind the power. Presumably the water temperature and flow rate are also fluctuating, although there have been no direct recordings of these. Pressure transducers in both the core and steam dome, however, have shown oscillations.

Threshold. Since it has been demonstrated that, other things being kept constant, increasing power results in an increasing oscillatory tendency one can talk about a power threshold—the power at which oscillations set in. Such a threshold is not sharply defined but can be taken to mean that power at which two or more cycles (of the same period) are occasionally self-induced in succession without noticeable phase shifting by boiling noise. Data on the thresholds shown in the table indicate correct trends, although an adequate knowledge of all the factors affecting the threshold is probably still lacking. Pressure, height of water above the core, fuel element time constant, water channel geometry, and void coefficient all have an influence. It is indeed fortunate for boiling-water reactors that the higher pressures with their increased thermal efficiency also are accompanied by large increases in the threshold for oscillation.

Oscillatory instabilities in electrically heated natural circulation boiling loops have been observed (*9*, *10*). These likewise have power density thresholds and frequencies comparable to those observed in reactors.

Kinetic Theory

The models in use by reactor physicists for instability analysis generally involve feedback loops between power and reactivity. A model (*11*) using a single series feedback loop and linear-

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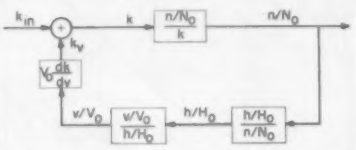

FIG. 4. Block diagram of boiling-water-reactor kinetics equations

ized one group kinetics equations is presented here as a very simplified example:*

$$\frac{l}{N_0}\frac{dn}{dt} = (1-\beta)k + \lambda l\frac{c}{N_0} - \beta\frac{n}{N_0}$$

$$\frac{l}{N_0}\frac{dc}{dt} = \beta k + \beta\frac{n}{N_0} - \lambda l\frac{c}{N_0}$$

$$\frac{1}{H_0}\frac{dh}{dt} = \frac{\alpha}{N_0}\frac{dn}{dt} - \alpha\frac{h}{H_0}$$

$$\frac{1}{V_0}\frac{dv}{dt} = \gamma\frac{h}{H_0} - \gamma\frac{v}{V_0}$$

$$k = \frac{dk}{dv}v + k_{in}$$

In the first two kinetics equations the symbols have their usual meanings. The neutron and delayed emitter densities are $N_0 + n$ and $C_0 + c$ respectively —i.e., the sum of their steady state values and small deviations therefrom. The heat transfer rate, $H_0 + h$ and the void fraction $V_0 + v$ are taken to have the time constants, $1/\alpha$ and $1/\gamma$ respectively. Finally the reactivity deviation from zero is the sum of the void effect and an input reactivity-driving function.

Taking the Laplace transform and solving the resulting linear algebraic equations for the systems transfer function gives the following result:

$$\frac{(n/N_0)/k_{in} =}{1 - \left(V_0\frac{dk}{dv}\right)\left(\frac{v/V_0}{h/H_0}\right)\left(\frac{h/H_0}{n/N_0}\right)\left(\frac{n/N_0}{k}\right)} \qquad \frac{(n/N_0)/k}{}$$

This also can be had by inspection of the block diagram representation of these equations in Fig. 4. Thus:

$$k_{in} + k_v = k = (n/N_0) \div \left(\frac{n/N_0}{k}\right)$$

* For a theory to be adequate, however, in explaining boiling-reactor behavior it must include the nonlinearities of the equations as well as a more accurate representation of the power feedback. The theory is also restricted for simplicity to frequencies in the resonance region.

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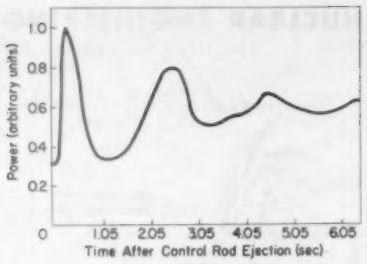

FIG. 5. Power transient following rapid ejection of control rod in Borax-IV

$$k_v = (n/N_0)\left(\frac{h/H_0}{n/N_0}\right)\left(\frac{v/V_0}{k/H_0}\right)\left(V_0\frac{dk}{dv}\right)$$

$$\therefore k_{in} = (n/N_0) \div \left(\frac{n/N_0}{k}\right) - (n/N_0)\left(\frac{h/H_0}{n/N_0}\right)\left(\frac{v/V_0}{h/H_0}\right)\left(V_0\frac{dk}{dv}\right)$$

or
$$(n/N_0)/k_{in} = \frac{(n/N_0)/k}{1 - \left(V_0\frac{dk}{dv}\right)\left(\frac{v/V_0}{h/H_0}\right)\left(\frac{h/H_0}{n/N_0}\right)\left(\frac{n/N_0}{k}\right)}$$

The system's gain can be expressed in terms of three functions:

(a) The zero-power reactor transfer function, $(n/N_0)/k$

(b) $V_0\frac{dk}{dv} \cong$ the reactivity in voids

(c) The power to void transfer function

$$\left(\frac{v/V_0}{h/H_0}\right)\left(\frac{h/H_0}{n/N_0}\right)$$

which, generally speaking, is not known, but would be $[1 + \alpha^{-1}s]^{-1}[1 + \gamma^{-1}s]^{-1}$ in the above formulation.

If, setting $k_{in} = 0$, one solves the differential equations for their eigenvalues, a damped oscillatory solution is found whose frequency depends on the reactor parameters. An example is shown in Fig. 3.

In the above expression for the transfer function, $(n/N_0)/k_{in}$, all terms on the right hand side can be slowly varying with frequency, and yet lead to a resonance—i.e., a very large maximum in $(n/N_0)/k_{in}$ occurring over a narrow range of frequencies. This is possible at frequencies for which the absolute value of the denominator becomes much less than 1. It is apparent that, when the reactivity in voids, $V_0\ dk/dv$, is sufficiently small, the denominator is unable to approach zero. At these low power levels no resonance should develop.

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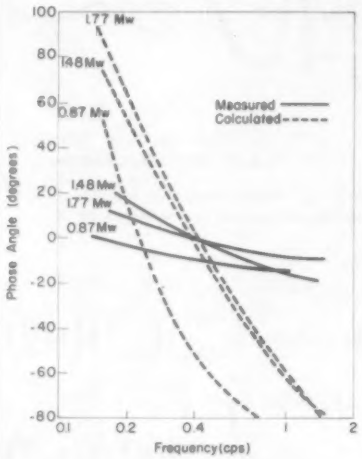

FIG. 6. Transfer-function phases for Borax-IV

The principal unknown in the above transfer function is the power to void transfer function, which can be expressed quite generally as follows:

$$\left(\frac{v/V_0}{h/H_0}\right)\left(\frac{h/H_0}{n/N_0}\right) = \left(\frac{v/V_0}{n/N_0}\right) = \Lambda \frac{\Pi(1 + T_i s)}{\Pi(1 + \tau_i s)}$$

where T_i and τ_i are time constants chosen to give agreement with experiment and Λ is the zero frequency value of $\left(\frac{v/V_0}{n/N_0}\right)$. These are, of course, functions of reactor geometry including hydraulic conditions, pressure, N_0, and n/N_0. For small n/N_0 this latter dependence is negligible, but as the region of sustained oscillations is approached, non-linear feedback must be expected.

Λ is quite well known theoretically and experimentally from years of zero frequency work. The time constants, on the other hand, are virtual unknowns. It should be possible, however, to evaluate them by boiling experiments in reactors, as well as electrically heated loops.

The frequently raised question as to whether boiling reactor instability is primarily a nuclear phenomenon or primarily a pure hydraulic instability can now be more precisely formulated. The latter will be the case when the T_i's and τ_i's are such as to allow v/V_0 to be virtually a self-sustained oscillation; the former will be the case when the transfer function, $(v/V_0)/(n/N_0)$, is slowly varying with frequency in the region of unstable reactor oscillations.

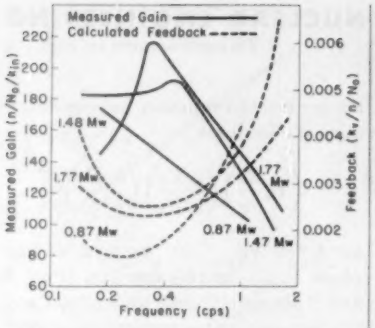

FIG. 7. Transfer-function amplitudes for Borax-IV

Experimental Approaches

Merely observing thresholds and amplitudes of self-induced oscillations does not give enough experimental information to understand instabilities. Two types of experiments,

(a) Withdrawal (rapidly) of a control rod while at power

(b) Oscillation of a control rod while at power

give significant amounts of additional information. These are analogous respectively to square wave and sine wave testing of electronic amplifiers. Both have been done on Borax IV (*4*) and EBWR with (b) found to be much more useful, as expected.

With regard to (a) the rapid ejection of the central control rod of Borax IV (while at an almost unstable power) gave the result shown in Fig. 5. Using the method proposed by Bethe (*12*) the transfer function, $(n/N_0)/k_{in}$, obtained from this figure was found to have a sharp resonance at 0.47 cps. This result was satisfactory, but could not be directly compared with the more accurate rod oscillator method, because the latter was run under different conditions.

In the oscillator technique, the transfer function, $(n/N_0)/k_{in}$, was obtained by dividing the power oscillation's amplitude by the average power and by the reactivity amplitude of the sinusoidally moving control rod (see Figs. 6 and 7). The phase shift, positive if the power leads the reactivity, is directly measured from two channel Brush recordings of the power and control rod position. A resonance, the height of which increases with power level, is obtained as one expects. These heights and half widths themselves offer excellent quantitive measures of the reactor's instability.

Using these measured transfer functions and the theoretical zero power

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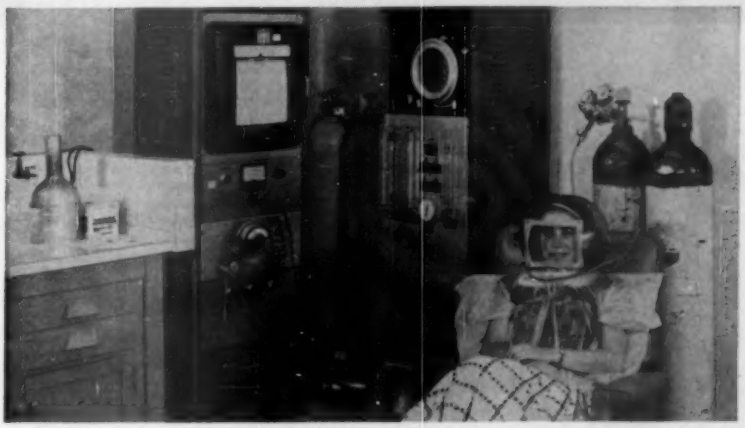

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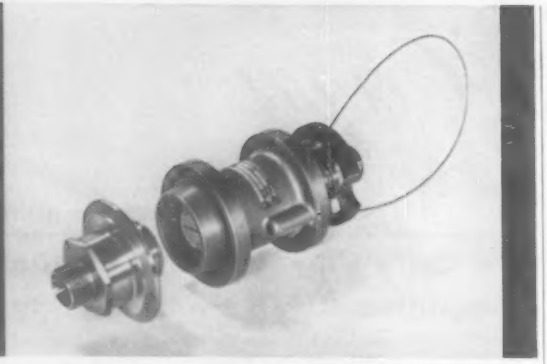

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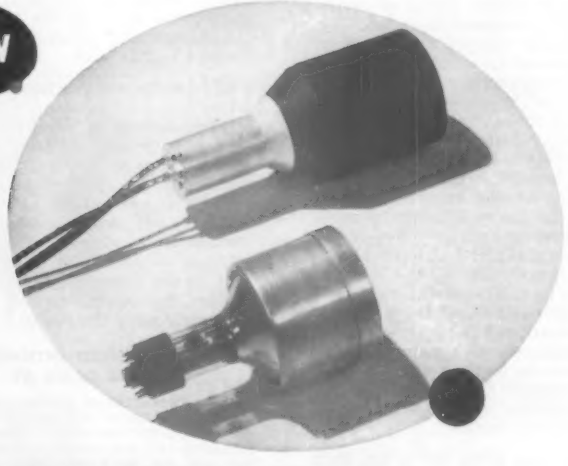

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reactor transfer function, one can determine the feedback,

$$-\left(V_0\frac{dk}{dv}\right)\left(\frac{v/V_0}{h/H_0}\right)\left(\frac{h/H_0}{n/N_0}\right)$$

or $k_v/(n/N_0)$. The amplitude and phase found for this function (Figs. 6 and 7) are not currently understood, and may be sensitive to experimental errors.* However the order of magnitude of the amplitude is understood, for if one divides the feedback by $V_0\frac{dk}{dv}$ ($\approx$ measured reactivity in voids), one obtains a number near unity for the remainder of the transfer function as expected from theory.

Predicting Instability

It is the hope that one eventually might be able to predict the unstable points of boiling reactors in the design stage for two reasons:

(a) It is a factor that may limit the maximum power;

(b) It determines the safety of the reactor under operating conditions.

Although it is not currently possible, the unstable points of operating boiling reactors may eventually be safely predicted by experiments at low power levels. The height and half width of the rod-oscillator-measured resonance, if any, is a direct measure of the self-oscillatory tendency. The resonance is observed to develop gradually as the power level increases. On the other hand the self-oscillatory tendency, especially at high pressures and large reactivities in voids, has been observed to develop very suddenly in some cases.

Some semiempirical techniques that can be used today to obtain information about the unstable point from a rod oscillator experiment are:

- An adequate theory of boiling reactor kinetics that describes both the rod oscillator experiment as well as the self-induced oscillation amplitude can have its unknown parameters determined by the rod oscillator.
- The reciprocal of the forced-oscillation transfer function at resonance

* Note added in proof: Recent EBWR transfer function measurements have had sufficient precision to accurately determine the feedback. Preliminary comparisons with the above theory have led to identification of the predicted time constants, $1/\alpha$ and $1/\gamma$; however there are indications that a two-time-constant theory may not be adequate in the resonance region.

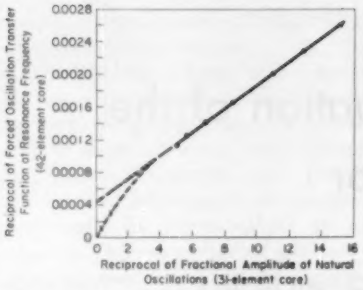

FIG. 8. Relation of forced-oscillation gain to self-induced oscillation amplitude for the same Δk in voids in Borax-IV at atmospheric pressure

plotted against the reciprocal of the fraction of the power oscillating (without the rod oscillator), as in Fig. 8, lends itself to extrapolation. Since the feedback transfer function divided by the Δk in voids is slowly varying with power, the forced oscillation gain at resonance can be predicted at higher powers, and hence also the self-oscillating fraction of the power.

- An approximate indication of the unstable power is simply had from a plot of the reciprocal forced resonant gain against power level. The power level at which this reciprocal extrapolates to zero should be unstable. (This procedure is analogous to reciprocal multiplication vs. amount of fuel curves in criticality experiments.)

* * *

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Hazards Evaluation of the Yankee Reactor

"My name is Clifford K. Beck . . . " With these words the head of AEC's Hazards Evaluation Branch began his testimony on the safety of the Yankee reactor. Because of the insight it provides into the design and operation of that reactor, NUCLEONICS presents this adaptation of Beck's testimony, with particular emphasis on novel aspects. The plant is being built by Yankee Atomic Electric Co. at Rowe, Mass.

The Yankee reactor will be generally similar to the Pressurized Water Reactor (PWR) now in operation at Shippingport, Pa. Unique features of the Yankee design, from a hazards-evaluation point of view, include the use of neutron-absorbing boric acid dissolved in the reactor coolant to assist the control rods in holding the reactor subcritical before the coolant has been heated to operating temperature, the existence of nucleate boiling in parts of the core at full power and the large buildup of plutonium in the core as a result of the long operating cycle.

Chemical Shutdown System

The chemical shutdown system injects the neutron-absorbing chemical into the reactor coolant system at shutdown to complement the neutron-absorbing rods and removes the chemical during startup. The system consists of a mixing tank and transfer pump for adding the boric acid to the reactor coolant system and two ion exchangers for removing it. About 1.6 gm of natural boron per liter of coolant should suffice to hold the clean cold reactor approximately 3% subcritical with at least one of the control rods withdrawn.

For shutdown, boric acid is injected, while the reactor is still at operating temperature and pressure, over a period of 30 min at a rate of about 100 gpm. For startup, boron is removed from the main coolant system by draining part of the reactor coolant and replacing it with fresh coolant. After the fresh coolant has circulated and mixed, this process is repeated. Only 5% of the boron remains in the coolant after about 11 hr of repeated diluting. The remaining boron is removed in the ion exchangers so that, after 22 hr, very little boron remains in solution.

The fuel enrichment used to give the required 10,000-hr core life at 392 Mw is 2.6%. With about 19% excess reactivity in the cold clean core, the control rods control about half, and the boron in the primary coolant controls the remaining half. In the hot, clean condition, with the boron removed and the control rods inserted, k_{eff} is <1, i.e., the reactor is subcritical with control rods alone.

Evaluation. Pressurized-water reactors have a high degree of inherent stability due primarily to the large negative temperature coefficient of reactivity associated with the large temperature change in density of the coolant-moderator superimposed on the somewhat smaller negative temperature coefficient of the fuel. A further stabilizing effect results from the negative void coefficient of reactivity that tends to reduce and limit the reactor in large transients accompanied by void formation due to boiling. The introduction of dissolved poison into the primary coolant tends to reduce the moderator's negative temperature and void coefficients.

The coolant-moderator coefficient is a property of both the fuel and water. The major contribution to this coefficient comes from the expansion of water and is therefore dependent on heat transfer between the fuel and the water. Since the fuel in this reactor is UO_2 in stainless-steel tubes, the effect is delayed because of the relatively poor heat transfer. Yankee has calculated that this coefficient is -2.7×10^{-5}/° F rise in coolant temperature at

room temperature and -2.7×10^{-4}/° F at operating temperature.

The addition of boron to the water decreases the coolant-moderator temperature coefficient because with heating the water will expand and displace poison from the reactor core. This is similar to withdrawing the control rods and causes the reactor power to increase. There are other effects, however, that partially compensate for this. For the concentrations of boron to be used in this reactor, it is my view that the composite coefficient will almost certainly be negative. With the maximum anticipated concentration of boron in the water, the values of this coefficient calculated by Yankee are -1.6×10^{-5}/° F at room temperature and -1.6×10^{-4}/° F at operating temperature.

These values placed on the temperature coefficient, and the effect of boron on this coefficient, appear to be reasonable. Thus, though the magnitude of the coefficient is reduced by the addition of boron, it will remain negative for the boron concentrations to be used in this reactor.

The fuel-temperature coefficient is fast acting and consists of two parts—the oxide expansion coefficient and the Doppler coefficient. The oxide expansion coefficient should be smaller than the Doppler coefficient by about a factor of ten and therefore need not be considered. Boron in the water has no appreciable effect on the magnitude of the Doppler coefficient, which is about -7.0×10^{-6}/° F, at both room and operating temperatures.

The void coefficient is similar to the coolant-moderator temperature coefficient in that it is a property of both the fuel and the water. Because of the relatively poor heat transfer between fuel and water, the effect of the void coefficient is delayed in its action, especially in a power transient. Because voids that are formed under actual operating conditions are concentrated in specific places in the core, the local void coefficient is more meaningful and useful than the over-all void coefficient. The latter coefficient can be calculated quite easily by assuming that the voids are formed uniformly throughout the water, but it is extremely difficult to calculate a local void coefficient.

The over-all void coefficient with no boron in the water has been calculated to be -0.3%/percent void, and with 1.6 gm of boron per liter in the coolant it is about -0.1%/percent void. Because experience has shown it is difficult to calculate these values, there have been cases in which a positive void cofficient was found where a negative one had been expected. If a positive coefficient should be found, it now appears that it probably would not be safe to proceed with operation. However, the value of the void coefficient is quite dependent on details of the fuel loading and spacing, and it is quite probable that, through minor revisions in the structural features of the core, negative void coefficients of sufficient magnitude can be obtained. The values of the void coefficient will be determined in advance of power operation by experiments in mockups and in the initial runs of the reactor itself.

Yankee has stated that it is not intended that the reactor will operate at power with the boron in the coolant. This minimizes the concern over the effect of the boron under normal conditions, but inadvertent reactor operation at power with boron in the coolant cannot be completely ruled out at this time.

Another possible problem is the inadvertent reduction in poison concentration, e.g., by precipitation or dilution, when it is needed for control. This could cause a reactor accident similar to a cold-water accident.

The possibility of an accident due to reconnecting an isolated loop in which the boron concentration is different from that in the core is minimized by an operating procedure that requires sampling and chemical analysis of the boron concentration before reconnecting a previously isolated loop. I agree with Yankee that slow-opening valves would limit the magnitude of these types of accidents to less than that of the maximum credible accident.

Core Design and Nucleate Boiling

The thermal and hydraulic design of the core is based on the following considerations: (a) local boiling in the subcooled liquid can be permitted in the core; (b) bulk boiling should not exist in the core; (c) the maximum heat flux in normal operation should not exceed 50% of the calculated burnout heat flux; (d) hot-channel factors should take into account variations in dimensions, flow distribution and neutron flux.

The hot channel factors between average and maximum values are 3.36 for the temperature rise through the core, 7.36 for the film drop and 5.17 for the heat flux. Based on these factors, the temperature of the coolant at the outlet of the hottest channel will be 599° F, or 37° F below the saturation temperature at 2,000 psia. The maximum metal-surface temperature is 642° F, or 6° F above the saturation temperature at 2,000 psia. The maximum heat flux is 4.49×10^5 Btu/ft²/hr. The hot channel factors also determine the maximum fuel-pellet temperature of 4,500° F—500° F below the estimated melting point of UO_2. The pressure drop across the core at the required velocity of 14 ft/sec is 14 psi. The total pressure drop from the inlet nozzle to the outlet nozzle is 28 psi.

The existence of nucleate boiling in the core is a feature that offers some unresolved aspects of safety. The full implications of the intended operational plan that will produce a continual condition of incipient boiling—that is, the power density, temperature and pressure conditions such that the boiling condition will be closely approached and possibly exceeded at the hottest local areas—have not been fully analyzed. I believe, however, that no unresolved hazards will exist when the analysis and the design have been completed, particularly if there is a strong negative void coefficient.

Core Life and Pu Buildup

Because this reactor is intended for the production of electric power, it is not expected to be subject to frequent startups and reloading. Present plans call for refueling shutdowns at intervals of more than a year. Thus, while the amount of fission products built up in the core will be greater than that of a testing or research reactor, the number of startups will be fewer and the probability of a startup accident will be correspondingly reduced. This is an important consideration since this type of accident is often considered the most likely.

A possible disadvantage of the long operating cycle is the unknown effect of a large buildup of plutonium. The Pu buildup may affect the fuel-temperature coefficient adversely and, thereby, reduce the magnitude of this inherent safety characteristic. Pu buildup may change the magnitude of the Doppler coefficient but its quantitative effect is not known at this time. However, Yankee states that, prior to operation, this effect will be investigated and the results will be used in determining the final design of the reactor. It is not anticipated that signifi-

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cant changes in design will be required because Pu buildup will probably cause only a small change in the Doppler coefficient, which is itself not very large.

Conclusions

There is reasonable assurance that a plant of the general type proposed by Yankee can be designed, constructed and operated at the proposed location without undue risk to the health and safety of the public. This is based on a review and analysis of information contained in the application, including the program of research and experimentation outlined by the application, and the experience which has been and is expected to be gained from design and operation of pressurized-water reactors.

The principal features of the reactor that appear to need extensive investigation are: (a) the use of soluble poison for control, (b) local boiling in the core and (c) the large plutonium buildup in the core. The final design of the reactor and its operating procedures must take into account the consequences of these features on reactor safety.

The applicant has outlined an extensive theoretical and experimental program for accomplishing this. I am convinced that the uncertainty associated with these features can be satisfactorily illuminated by programs such as those outlined by the applicant and that there is no reason now apparent for believing that inherently unsafe features will exist in Yankee.

A Simplified P_3 Approximation Method for Calculating Thermal Utilization

By EARL M. PAGE* and RAYMOND L. MURRAY
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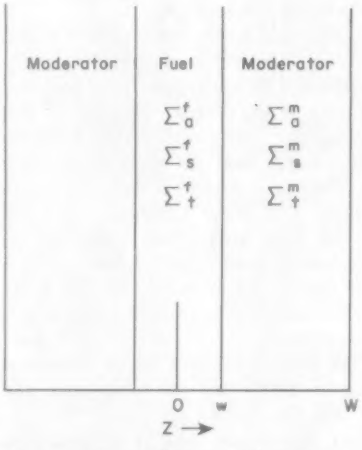
The accurate calculation of the thermal utilization f for a heterogeneous thermal reactor with large macroscopic cross section for the fuel region requires the use of transport theory. Diffusion theory is not adequate in many reactors because of enrichment, excess fuel for long reactor life or use of burnable poison. Calculations by the conventional form of the spherical harmonic (P_n) approximations of transport theory (*1*), however, are laborious.

In this simplified method, the P_3 approximation is reformulated for plate systems in such a way that the thermal utilization is computed directly in terms of the F and E factors (*2*) of diffusion cell theory. That the absorption cross section of the moderator is small compared with its scattering cross section is the only simplifying approximation made. This condition will be met for a practical heterogeneous reactor.



Schematic diagram of cell of a plate-type fuel element

Example

Consider the cell of a plate-type fuel element for which the absorption, scat-

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tering and transport cross sections are as indicated in the figure. The thermal utilization, defined as (absorption in fuel)/(total absorption in cell), is written

$$\frac{1}{f} = \frac{(W - w)\sum_a^m}{w\sum_a^f} F + E$$

where F and E are modified versions of the familiar functions of diffusion theory.

The new working formulas are displayed below, along with a numerical illustration based on an assembly for which the half widths of the fuel region and moderator are $w = 0.02921$ cm, $W - w = 0.60816$ cm, and for which cross sections (in cm^{-1}) are $\sum_a^f = 2.5066$, $\sum^f = 3.3330$, $\sum_T^f = \sum_a^f + \sum_t^f = 3.3238$, $\sum_a^m = 0.05282$, $\sum^m = 2.02312$ and $\sum_T^m = \sum_a^m + \sum_t^m = 1.95342$.

The value of f obtained by the formal P_3 approximation is 0.66249, a difference of only 0.2% from the result of the foregoing simplified method. In contrast, f as computed by ordinary diffusion theory is 0.67705, which corresponds to a discrepancy of 2.2% in f and a difference of approximately 7% in fuel-plate absorption. The simplified method lends itself readily to desk calculator work with about one hour required for the determination of one value of thermal utilization.

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2. S. Glasstone, M. C. Edlund, "The Elements of Nuclear Reactor Theory," p. 264 (D. Van Nostrand Co., Inc., Princeton, New Jersey, 1952)

$$\left[(k^f)^2 - 3\sum_a^f\sum_T^f\right]\left[9(k^f)^2 - 35\left(\sum^f\right)^2\right] = 28(k^f)^2\sum_a^f\sum^f$$

$$k_1{}^f = 3.6549$$

$$k_3{}^f = 8.9904$$

$$k_1{}^m \simeq \sqrt{3\sum_a^m\sum_t^m} = 0.548789$$

$$k_3{}^m \simeq \frac{\sqrt{35}}{3}\sum^m = 3.98965$$

$$F_1 = k_1{}^f w \coth k_1{}^f w = 1.00380$$

$$F_3 = k_3{}^f w \coth k_3{}^f w = 1.02288$$

$$E_1 = k_1{}^m(W - w) \coth k_1{}^m(W - w) = 1.03685$$

$$E_3 = k_3{}^m(W - w) \coth k_3{}^m(W - w) = 2.46454$$

$$r_{21}{}^f = \frac{14\sum_a^f\sum^f}{35\left(\sum^f\right)^2 - 9(k_1{}^f)^2} = 0.435485$$

$$r_{23}{}^f = \frac{1}{2}\left[\frac{3\sum_a^f\sum_T^f}{(k_3{}^f)^2} - 1\right] = -0.345387$$

$$r_{23}{}^m = \frac{1}{2}\left[\frac{3\sum_a^m\sum_T^m}{(k_3{}^m)^2} - 1\right] = -0.490277$$

$$\gamma_2 = \frac{5}{3}\left(\sum^f\right)^2(r_{21}{}^f - r_{23}{}^f) = 14.4577$$

$$\gamma_3 = r_{21}{}^f F_1 - r_{23}{}^f F_3 = 0.790429$$

$$A = (F_3 - F_1)\frac{r_{21}{}^f\left[\sqrt{35}\sum^f k_3{}^m(W - w)F_1 + 3(k_1{}^f)^2 w E_3\right]}{\sqrt{35}\sum^f k_3{}^m(W - w)\gamma_3 + 7wE_3\gamma_2} = 0.009379$$

$$F = F_1 + A = 1.01318$$

$$B = \frac{(E_3 - E_1)\sum_a^m r_{23}{}^f\,[3(k_3{}^f)^2\gamma_3 - 7F_3\gamma_2](W - w)}{\sum_a^f r_{23}{}^m\left[\sqrt{35}\sum^f k_3{}^m(W - w)\gamma_3 + 7wE_3\gamma_2\right]} = 0.025191$$

$$E = E_1 + B = 1.06204$$

$$f = 0.66377$$

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Perturbation theory techniques help in . . .

Predicting Reactivity at High Burnup

By BERTRAM WOLFE
Atomic Power Equipment Department,
Vallecitos Atomic Laboratory
General Electric Co., San Jose, California

As a reactor operates, changes in composition occur in its core. Fuel is depleted, other materials of high cross section are burned, and xenon and other fission products build up. These changes affect reactivity and the reactor designer must be able to evaluate their effects in order to optimize reactor design.

The brute-force approach to this problem has been to make a series of standard reactor calculations, each one corresponding to a different time during the burnup cycle. We describe here a simple perturbation technique that can be used to calculate burnup effects taking into account the spatial variation of the burnup.* The complete reactor operating history (see Fig. 1) can be followed and adjustments in initial fuel loading can be made, all on the basis of a single standard computation of a uniformly loaded core. The technique is particularly well suited for determining the effect of a burnable poison and the optimum poison and fuel loading.

As with all perturbation calculations, an "exact" solution is not obtained. However the method gives quite accurate results for many, if not most, highly enriched thermal reactors.

Perturbation Method

Although burnup causes marked changes in flux levels and core composition, the *shape* of the thermal flux distribution is in many practical cases not greatly affected. For instance, K. Cohen (*2*) has used one-group treatment to show that the flux shape in a bare reactor does not change appreciably, provided that $\frac{\Delta k_{\infty_{max}}}{k_{\infty_c} - 1} < 4$ where $\Delta k_{\infty_{max}}$ is the maximum change in k_∞ at any point in the reactor, and k_{∞_c} is the critical value of k_∞. Cohen points out that this is actually a weak condition.

* The inadequacy of assuming a uniform "average" core change is well known (*1*).

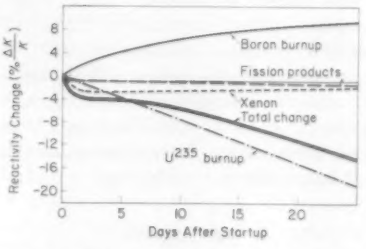


FIG. 1. Change in reactivity with time in high-flux test reactor as calculated by perturbation method. Separate presentation of different reactivity effects shows how boron burnable poison reduces total reactivity change by 8.5%

In the appendix we show with two-group treatment that, if the effect of burnup changes on the neutron economy in a core region is small compared to the neutron leakage from the region, the thermal flux shape will not change significantly. Cohen's results ($k_\infty - 1$ is the leakage) indicate this conclusion may be conservative. In any case, since highly enriched reactors have neutron leakages of 10%–40%, a considerable change in the core parameters is required to alter the flux shape.

The fact that the thermal flux distribution remains fairly constant during the reactor cycle suggests that perturbation theory can be used to evaluate burnup effects (*3*). To see this, consider the solution of the eigenfunction problem for a reactor core, using simple two-group theory (the method applies just as well for three or more groups). With no resonance capture, the diffusion equations may be written

$$\begin{aligned} -D_1\nabla^2\phi_1 + \Sigma_{SD}\phi_1 &= \nu\,\Sigma_f\,\phi_2 \\ -D_2\nabla^2\phi_2 + \Sigma_a\phi_2 - \Sigma_{SD}\phi_1 &= 0 \end{aligned} \quad (1)$$

where standard notation is used. One seeks the lowest eigenvalue ν and its eigenfunctions ϕ_1 and ϕ_2 which depend upon the physical properties of the reactor.

To do perturbation calculations, the adjoint fluxes ϕ_1^+ and ϕ_2^+ must also be available. The adjoint fluxes are the solution of the adjoint equations.

$$\begin{aligned} -D_1\nabla^2\phi_1^+ + \Sigma_{SD}\phi_1^+ - \Sigma_{SD}\phi_2^+ &= 0 \\ -D_2\nabla^2\phi_2^+ + \Sigma_a\phi_2^+ &= \nu\,\Sigma_f\phi_1^+ \end{aligned} \quad (2)$$

For a method of obtaining adjoint fluxes with computer codes that calculate normal fluxes see p. 121.

Assume that Eqs. 1 and 2 have been solved for the initial uniformly loaded core. Then, as the reactor operates, Σ_a will change to $\Sigma_a + \delta\Sigma_a$, Σ_f to $\Sigma_f + \delta\Sigma_f$, ϕ_1 to ϕ'_1, ϕ_2 to ϕ'_2, and ν to ν'. $\delta\Sigma_a$ and $\delta\Sigma_f$ are functions of position. In highly enriched thermal reactors, the changes in the diffusion coefficients and in Σ_{SD} are extremely small and will be neglected.

According to perturbation theory, the change in ν (the number of neutrons per fission required for criticality) produced by a change in the reactor parameters can be written

$$\delta\nu = \frac{\int \phi_2^+\delta\Sigma_a\,\phi'_2 - \nu'\int \phi_1^+\,\delta\Sigma_f\,\phi'_2}{\int \phi_1^+\,\Sigma_f\,\phi'_2} \quad (3)$$

where $\delta\nu = \nu' - \nu$.

Equation 3 is exact. If we assume that the thermal flux shape in the reactor does not change during the running cycle, then we can replace the unknown flux ϕ'_2 with the known flux ϕ_2. Using this approximation we derive the reactivity change produced by each of the following effects:

• **Fuel burnup.** Let Σ_{25} be the macroscopic absorption cross section of the fuel and σ_{25} be the microscopic absorption cross-section of the fuel. Then at time t, for any point in the core

$$\Sigma_{25} = \Sigma_{25}^0\, e^{-\sigma_{25}\int_0^t \phi_2(t)\,dt} \quad (4)$$

where Σ_{25}^0 is Σ_{25} at $t = 0$
and ϕ_2 is the thermal flux. The change in Σ_{25} is then

$$\begin{aligned} \delta\Sigma_{25} &= \Sigma_{25} - \Sigma_{25}^0 \\ &= -\Sigma_{25}^0\,[1 - e^{-\int\sigma_{25}\phi_2(t)\,dt}] \quad (5) \\ \delta\Sigma_f &= -\Sigma_f^0\,[1 - e^{-\int\sigma_{25}\phi_2(t)\,dt}] \quad (6) \end{aligned}$$

Substituting Eqs. 5 and 6 into Eq. 3 yields the change in ν due to the burnup

$$-\delta\nu = \frac{\{\int \phi_2^+\Sigma_{25}^0[1 - e^{-\int\sigma_{25}\phi_2(t)\,dt}]\phi_2 - \nu'\int \phi_1^+\Sigma_f^0[1 - e^{-\int\sigma_{25}\phi_2(t)\,dt}]\phi_2\}}{\int \phi_1^+\Sigma_f^0\phi_2} \quad (7)$$

where ϕ'_2 has been replaced by ϕ_2, since the shape of ϕ_2 is assumed not to change. Although the shape of ϕ_2 does

not change, its magnitude does. Therefore, $\phi_2(t)$ can be written

$$\phi_2(t) = \phi_2 c(t) \tag{8}$$

where ϕ_2 is the initial flux at $t = 0$, and $c(t)$ is dependent only on time and not on position. Using Eq. 8, expression 7 can be rewritten

$$\frac{\delta k}{k} = -\frac{\delta \nu}{\nu} = \frac{\int \phi_2^+ \Sigma_{25}^0 (1 - e^{-\phi_1 \sigma_{25} \int c dt}) \phi_2}{\nu \int \phi_1^+ \Sigma_f^0 \phi_2} - \frac{\nu \int \phi_1^+ \Sigma_f^0 (1 - e^{-\phi_1 \sigma_{25} \int c dt}) \phi_2}{\nu \int \phi_1^+ \Sigma_f^0 \phi_2} \tag{9}$$

Equation 9* represents the reactivity change due to fuel burnup. $\int c\, dt$ is easily calculated (see box) so that all that is required for the evaluation of Eq. 9 is a knowledge of the initial and adjoint flux distributions. For short term effects (small burnup) the exponents in Eq. 9 can be expanded. In general, Eq. 9 must be integrated numerically; but in simple core geometries, this is not a difficult task and in complicated core geometries, the work and expense involved is small compared to that required by other methods.†

• Burnup of other materials. The effect of the burnup of other materials is calculated exactly as described for U^{235}, except of course, that the cross-sections for these materials are used and not the U^{235} cross-sections. Thus, for boron:

$$\delta \nu = \frac{-\int \phi_2^+ \Sigma_B^0 (1 - e^{-\sigma_B \phi_2 \int c dt}) \phi_2}{\int \phi_1^+ \Sigma_f^0 \phi_2} \tag{10}$$

where σ_B is the microscopic boron cross section and Σ_B^0 is the macroscopic boron cross-section at startup.

• Xenon buildup. At equilibrium the macroscopic xenon absorption cross section can be written (4) as

$$\delta \Sigma_x = \frac{\Sigma_f \sigma_2 (\gamma_1 + \gamma_2) \Sigma_{25} \phi_2}{\Sigma_{25} (\lambda_2 + \sigma_2 \phi_2)} \tag{11}$$

where $\delta \Sigma_x$ = the xenon macroscopic absorption cross section and the rest of the notation follows (4). $\delta \Sigma_x$ can be inserted in Eq. 3 for $\delta \Sigma_a$ to determine the reactivity effect of equilibrium xenon.

The change in equilibrium xenon effect with time can be obtained by using Eq. 4 in Eq. 11 for Σ_{25} and substituting $(\lambda_2 + \sigma_2 \phi_2 c)$ for $(\lambda_2 + \sigma_2 \phi_2)$. With high flux reactors (i.e., test reactors), the arithmetic can be eased. For a flux of the order of 4×10^{14} n/cm²/sec, Eq. 11 yields

$$\delta \Sigma_x = 0.049\, \Sigma_{25} \tag{12}$$

This relation has only a very weak dependence on flux. The use of Eq. 12 considerably simplifies the evaluation of Eq. 3.

• Other fission products. The buildup of fission products other than xenon in highly enriched reactors has been studied in detail by Deutsch (5).

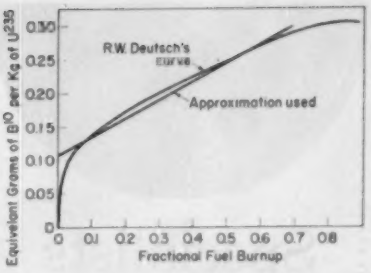


FIG. 2. Buildup of fission products (less xenon) with fuel burnup

Figure 2 is a plot of Deutsch's data. In computing the fission product effects as a function of time, Deutsch's curve can be approximated as shown in Fig. 2 by an initial step and a straight line. Then

$$\delta \Sigma_{fp} = 0.0152\, \Sigma_{25}^0 - 0.0379\, \delta \Sigma_{25} \tag{13}$$

Although this approximation is not necessary, it eases the calculation. The effect of the fission products on reactivity is found by substituting Eq. 13 in Eq. 3. The effect of the first term in Eq. 13 can be evaluated immediately. The effect of the second term as a function of time can be obtained by multiplying the reactivity effect previously obtained for the change in Σ_{25} (see Eq. 9) by 0.0379.

Control-Rod Effects

In the calculations thus far described, the effect of control-rod motion has been explicitly neglected. In almost all cases of interest, the neglect of control-rod motion will cause an underestimate in the length of the running cycle. This is because control rods are usually operated so as to increase burnup in regions of lower weight thus keeping the hot spot factor low and lengthening the running cycle as much as possible.

Moreover the integral nature of the perturbation calculation, minimizes the effect of neglecting control rod motion in most cases. This can be seen by noting that the perturbation expressions involve integrals over the core. If the fluxes and adjoint fluxes do not change rapidly, there can be large local alterations in the burnup distribution without the integrals (i.e., the reactivity) being greatly affected.

In those cases, where the change in burnup distribution caused by control rod motion does have an appreciable effect on reactivity the methods outlined in this paper can still be used if a

* Equation 9 assumes that $\delta\nu$ is so small that $\nu^1 \approx \nu$. For more accuracy Eq. 3 can be solved explicitly for ν^1.

† E.g., doing a series of successive calculations, or exact solution of the time dependent equations.

How to Evaluate c(t)

The perturbation technique assumes that the magnitude but not the shape of the thermal flux distribution changes with time. Mathematically this is expressed by writing the flux at time t as $\phi(x,t) = \phi_0(x)c(t)$, where ϕ_0 is the initial flux distribution and c is a time dependent normalizing factor. To evaluate $c(t)$ we observe that the energy put out by the reactor is proportional to the amount of fuel burned up. Thus, at time t after startup

$$\int \Sigma_{25}^0 (1 - e^{-\sigma_{25} \phi_2 \int_0^t c\, dt}) dv = K \int_0^t P\, dt \tag{I}$$

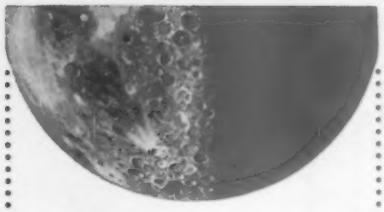
where P is the reactor power, K is a constant relating fuel burnup to energy and the integration on the left is performed over the core volume. Equation I can be evaluated to give the time t corresponding to a given value of $\int_0^t c\, dt$.

Assume now, that, after Eq. I has been evaluated for a particular loading characterized by Σ_{25}^0, the loading is increased to the value $U\Sigma_{25}$. Then ϕ_2 is changed to ϕ_2/U and Eq. (I) becomes

$$\int U \Sigma_{25}^0 (1 - e^{-\sigma_{25} \phi_2 / U \int c\, dt}) dV = K \int_0^t P\, dt$$

$$\int \Sigma_{25}^0 (1 - e^{-\sigma_{25} \phi_2 \int^{t/U}}) dV = KP(t/U) \tag{II}$$

where P_{avg} is the average power level over the time-interval t. Comparing Eq. II with Eq. I and assuming that the power level is constant, one sees that the exponent in the integral must have the same value at t/U as it previously had at t. In other words, if $\phi_2 \int_0^t c\, dt = f(t)$ then a change in Σ_{25}^0 by the factor U changes $f(t)$ to $f(t/U)$.



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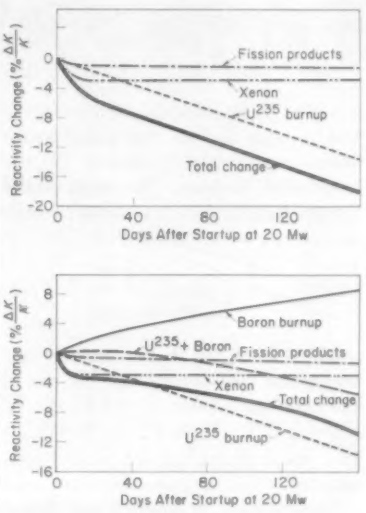


FIG. 3. Burnup calculations on proposed reactor using stainless-steel fuel elements: (a) calculations show original core would need 13% $\Delta k/k$ excess reactivity for 100-day cycle; only 10% was estimated to be available. (b) Calculations show addition of burnable poison to core gives 140-day cycle for only 9% $\Delta k/k$

reasonable estimate of the final core composition can be made.

Sample Applications

Figure 1 shows the results obtained with this method for a proposed test reactor that uses a boron burnable poison. The ability to display separately the reactivity changes due to the various contributing sources is an attractive feature of the method. From Fig. 1, for example, one can see very clearly that the boron reduces the reactivity excursion by 8½% after 20 days of operation.

The effect of a change in the loading can also be easily calculated. Assume that the running cycle of Fig. 1 is unsatisfactory; the designer may, for instance, wish to extend the running cycle. Now it is plain that a reduction in the loss of reactivity by burnup can be achieved by increasing the initial content of boron. Of course, the difficulty is that an initial increase of boron calls for an initial increase of U^{235} to provide the required reactivity at startup. The situation faced is that a change in boron requires a change in U^{235}, which in turn changes the effect of the boron, etc. The methods developed above lead to a simple means of solution. Examine the effect of increasing the boron content by the factor B and the uranium by the factor U. From Eq. 10, the net result (for a given $\int c\,dt$) is to multiply the effect of the boron by the factor B/U. On the other hand, both the numerator and the denominator of Eq. 7 are multiplied by U, so that for a given $\int c\,dt$, the effect of U^{235} burnup does not change. The same holds true for fission product effects and for the xenon effect in high flux reactors where Eq. 12 can be used. However, for low flux reactors, the change in loading will change the flux level and Eq. 11 must be re-evaluated.

Due to the change in flux level, the value of $\phi_2 \int_0^t c\,dt = f(t)$ will be changed for a given period of operation, t. The box shows that if the initial uranium content is multiplied by U, then $\phi_2 \int_0^t c\,dt = f(t)$ will be changed to $f(t/U)$. In other words, the time scale must be changed by the factor U in order to keep $\phi_2 \int c\,dt$ the same as before the change.

To sum up then, if the boron is increased by the factor B and the fuel by the factor U, the time scale of Fig. 1 should be multiplied by U and the value of the boron curve by B/U. The exception to this procedure is the xenon effect in the case of a low-flux reactor.*

Figure 3 illustrates the use of the method in the preliminary design of a reactor using stainless steel fuel elements. Figure 3a shows the running cycle in the initial design where burnable poisons were not employed. It can be seen that 13% excess reactivity is required to achieve a 100-day running cycle. In the design proposed, it was doubtful that there would be more than 10% shim control available. With the methods described in this paper, a second loading with a burnable poison (boron) was found that had an initial k_{∞} of 1.09 and in which boron burnup compensated for uranium burnup at the start of the cycle. The results are shown in Fig. 3b—a 140-day cycle was achieved with 9% control in $\Delta k/k$.

An interesting check of the perturbation method is shown in Figs. 4 and 5. Here, a reactor using aluminum fuel elements was being designed. Equations 1 and 2 for the uniform core were solved on an IBM-650 computer to obtain the fluxes and adjoint fluxes for the initial loading (no burnable poison).

* In a low-flux reactor, the change in the xenon effect can be roughly estimated, the core loadings adjusted as desired, and then the xenon can be recalculated using Eq. 11. The change in the xenon effect can be obtained roughly on the basis of the change in average flux using (3) p. 568.

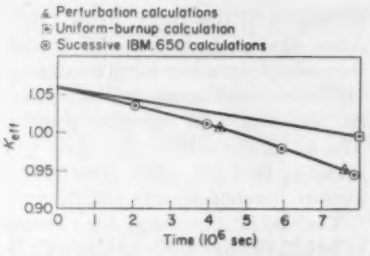


FIG. 4. Results of perturbation method for reactor with Al elements are compared with uniform burnup calculation and to series of successive IBM-650 calculations. Notice excellent agreement between perturbation and the successive calculation results

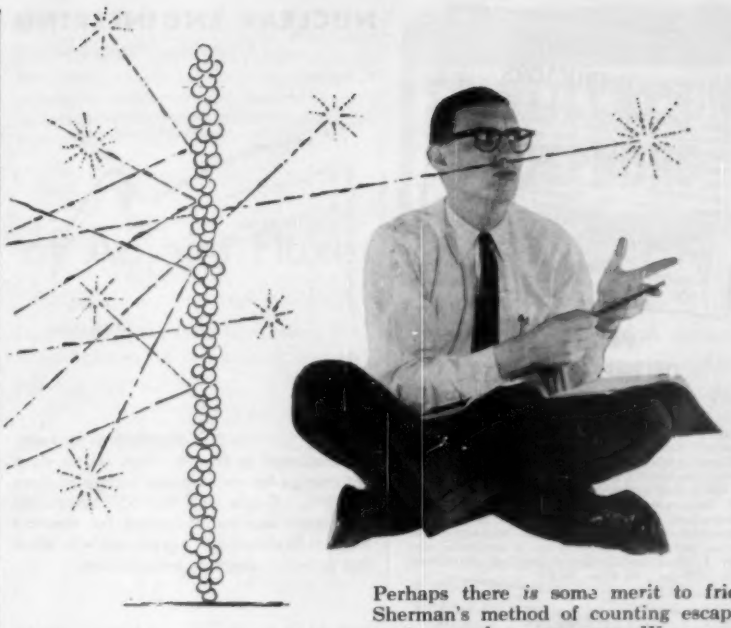
The reactivity versus time (Fig. 4) was then calculated using the perturbation method. To check this technique, the total time of operation (30.27% average burnup) was divided into four equal periods and four successive two-group calculations were performed. In these, the core was broken into seven annular regions and the cross sections in each region calculated using the flux from the previous calculation. The reactivity calculated as a function of time in this way is compared in Fig. 4 with the results of perturbation method.

Figure 5 compares the flux distribution obtained from the last of the four calculations with the initial flux distribution. Also shown is the final flux distribution resulting from a single calculation that used cross sections based on a burnout having the original flux shape. The change in reactivity calculated by the perturbation technique

Comparison of k_{eff} Calculated by Different Methods

	Perturbation method	*Successive calculations*	*Uniform burnup*
Loading 1			
(3.92 kg U^{235})			
Start of cycle*	1.060	1.060	1.060
After 30.3% burnup	0.946	0.945	1.00
Loading 2			
Start of cycle	1.060	1.060	1.060
After 28.4% burnup	1.013	1.0125	1.038

* The initial calculation is used for all three methods.



it's the little things that count

Perhaps there *is* some merit to friend Sherman's method of counting escaping neutron and gamma rays. We are certainly not going to scoff at what may well be experimental originality in the field of nuclear research. However, we opine that Sherm's calculations are a bit too extreme. Accuracy might better be achieved by one of our DETECTOLAB® Nuclear Systems.

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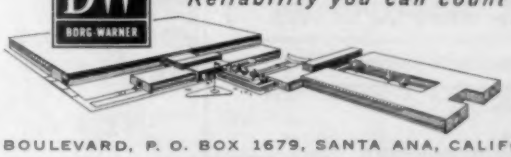

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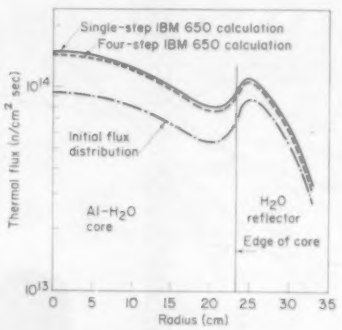

FIG. 5. Thermal-flux distributions for reactor discussed in Fig. 4. Flux shape does not change for an average burnup of close to 30%. Single step IBM-650 calculation uses cross sections computed for constant thermal flux shape. Agreement with initial flux provides check of perturbation.

was $\Delta k/k = 10.75\%$, by the successive calculation, method, $\Delta k/k = 10.85\%$.

Following this the core loading was changed and burnable poison added. Using the perturbation method, a loading was found that had an initial k_{eff} of 1.06 and the boron concentration was set so that the boron burnup compensated for the uranium burnup at the start of the cycle. The k_{eff} after 28.4% burnup was calculated, using the techniques of this paper, to be 1.013. After the perturbation calculations were complete, a new set of successive IBM-650 calculations were performed for the core with burnable poisons. The k_{eff} at the start of the cycle was found to be 1.060, while after 28.9% average burnout k_{eff} was 1.0125.

The table compares the results obtained using the techniques in this paper, the successive calculation method and the result obtained assuming uniform burnup.

It should be noted that the successive calculation technique required ten IBM-650 solutions of the complete reactor system. The perturbation calculations required only one IBM-650.

* * *

It is a pleasure to acknowledge the work of Dr. D. Fischer and Mr. M. Weiss who have performed a number of the detailed perturbation calculations described in this paper and extended the use of these methods to cases not discussed.

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Appendix—Thermal Flux Distribution Stability

Assume that the absorption and fission cross-sections in a reactor are changed so that:

$$\Sigma_a \rightarrow \Sigma_a + \delta\Sigma_a \quad (1)$$

$$\nu\Sigma_f \rightarrow \nu\Sigma_f + \delta(\nu\Sigma_f) \quad (2)$$

Let the unperturbed fluxes be ϕ_1 and ϕ_2 and let the perturbed fluxes be $\beta\phi_1$ and $\alpha\phi_2$. Where β and α are functions of position.

Then the diffusion equations for the perturbed reactor are:

$$-D_1\nabla^2\beta\phi_1 + \Sigma_{SD}\beta\phi_1 - \delta(\nu\Sigma_f)\alpha\phi_2 - \nu\Sigma_f\alpha\phi_2 = 0 \quad (3)$$

$$-D_2\nabla^2\alpha\phi_2 + \Sigma_a\alpha\phi_2 + \delta\Sigma_a\alpha\phi_2 - \Sigma_{SD}\beta\phi_1 = 0 \quad (4)$$

Solving Eq. 4 for β yields:

$$\beta = \frac{-D_2\nabla^2\alpha\phi_2 + \alpha\Sigma_a\phi_2 + \alpha\delta\Sigma_a\phi_2}{\Sigma_{SD}\phi_1} \quad (5)$$

Insert Eq. 5 in Eq. 3 and arrange terms to obtain:

$$\tau\nabla^2(-D_2\nabla^2\alpha\phi_2 + \Sigma_a\alpha\phi_2) + D_2\nabla^2\alpha\phi_2 + \alpha\left\{(\nu\Sigma_f - \Sigma_a)\phi_2 + \left[\delta(\nu\Sigma_f)\phi_2 - \delta\Sigma_a\phi_2 + \frac{\tau\nabla^2\delta\Sigma_a\alpha\phi_2}{\alpha}\right]\right\} = 0 \quad (6)$$

Equation 6 is the critical equation determining the perturbed thermal flux $\alpha\phi_2$ and the corresponding eigenvalue $\nu + \delta\nu$. Now it should be noted from Eq. 6 that the last terms in the brackets ([ ]) are the only terms that contain the changed cross-sections and if the terms in the brackets add up to zero everywhere, the equation for $\alpha\phi_2$ is the same as the equation for ϕ_2. In this case, therefore, α must be a constant and the thermal flux distribution is unchanged by the perturbations. [However, as shown by Eq. 5, even if the terms in the brackets do add up to zero, there is a change in the fast flux providing $\delta\Sigma_a \neq 0$.]

The physical significance of the terms in the brackets is plain. Assuming that α is constant and made equal to 1, the term $\delta(\nu\Sigma_f)\phi_2$ is the excess number of neutrons produced over the unperturbed case; the term $\delta\Sigma_a\phi_2$ is the number absorbed and the term $\tau\nabla^2\delta\Sigma_a\phi_2$ is the excess (fast) neutron leakage due to the change in shape of the fast flux. If these terms add up to zero, therefore, the neutron economy will still be balanced without changing the thermal flux shape.

Equation 6 indicates that the criterion for measuring the severity of a perturbation on the thermal flux distribution involves the comparison of the magnitude of the terms in the brackets with $(\nu\Sigma_f - \Sigma_a)\phi_2$. But $(\nu\Sigma_f - \Sigma_a)\phi_2$ is equal to the number

of neutrons per second leaking from a unit volume of the reactor. Thus, the criterion for thermal flux distribution stability can be stated as follows:

The effect of the perturbations on the neutron economy [as indicated by the terms in the brackets in Eq. 6] should be small compared to the leakage from the reactor.

This criterion is physically reasonable since, if the leakage is high compared to the perturbing effect, only a small change in leakage (and thus in flux shape) is required to balance the neutron economy against the perturbation.

Easy Computation of Adjoint Fluxes

By BERTRAM WOLFE
Atomic Power Equipment Department
Vallecitos Atomic Laboratory
General Electric Co., San Jose, California

If in your multigroup code fissions occur only in the last group* and fission neutrons enter only the top group, you can use the same code to compute adjoint fluxes simply by switching some of the input data. To see how this works consider a typical three-group program in which fissions occur only in the third group and neutrons are born only in the first group. The equations are

$$\begin{aligned}\nabla \cdot D_1\nabla\phi_1 - \Sigma_{r_1}\phi_1 + \nu\Sigma_{f_3}\phi_3 &= 0\\ \nabla \cdot D_2\nabla\phi_2 - \Sigma_{r_2}\phi_2 + \Sigma_{sD_1}\phi_1 &= 0\\ \nabla \cdot D_3\nabla\phi_3 - \Sigma_{r_3}\phi_3 + \Sigma_{sD_2}\phi_2 &= 0\end{aligned} \quad (1)$$

where, for group n, D_n is the diffusion coefficient, Σ_{r_n} is the removal cross-section, Σ_{sD_n} is the slowing down cross-section, Σ_{f_n} is the fission cross-section and ϕ_n is the flux.

In matrix notation Eqs. 1 become

$$\nu\mathsf{J}\Phi - \mathsf{K}\Phi = 0 \quad (2)$$

where the vector

$$\Phi \text{ is } \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix} \quad (3)$$

the matrix J is

$$\begin{pmatrix}0 & 0 & \Sigma_{f_3}\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix} \quad (4)$$

and the matrix K is

$$\begin{pmatrix}-\nabla\cdot D_1\nabla + \Sigma_{r_1} & 0 & 0\\ -\Sigma_{sD_1} & -\nabla\cdot D_2\nabla + \Sigma_{r_2} & 0\\ 0 & -\Sigma_{sD_2} & -\nabla\cdot D_3\nabla + \Sigma_{r_3}\end{pmatrix} \quad (5)$$

* If your problem has fissions in more than one group and fission neutrons enter more than one group, the above procedure can still be used by making additional input substitutions. Consider an N group problem where N is the last (thermal) group and χ_n is the fraction of fission neutrons entering group n. To calculate the adjoint fluxes make the following additional substitutions

$$\begin{aligned}\chi_N &\to \Sigma_{f_1} & \Sigma_{f_N} &\to \chi_1\\ \chi_{N-1} &\to \Sigma_{f_2} & \Sigma_{f_{N-1}} &\to \chi_2\\ \chi_1 &\to \Sigma_{f_N} & \Sigma_{f_1} &\to \chi_N\end{aligned}$$

In perturbation calculations (see p. 116), in addition to Φ the adjoint flux Φ^+, must be found from

$$\nu\mathsf{J}^+\Phi^+ - \mathsf{K}^+\Phi^+ = 0 \quad (6)$$

where the matrix J^+ is

$$\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ \Sigma_{f_3} & 0 & 0\end{pmatrix} \quad (7)$$

and the matrix K^+ is

$$\begin{pmatrix}-\nabla\cdot D_1\nabla + \Sigma_{r_1} & -\Sigma_{sD_1} & 0\\ 0 & -\nabla\cdot D_2\nabla + \Sigma_{r_2} & -\Sigma_{sD_2}\\ 0 & 0 & -\nabla\cdot D_3\nabla + \Sigma_{r_3}\end{pmatrix} \quad (8)$$

The set of equations represented by Eq. 6 can be written

$$\begin{aligned}\nabla \cdot D_3\nabla\phi_3^+ - \Sigma_{r_3}\phi_3^+ + \nu\Sigma_{f_3}\phi_1^+ &= 0\\ \nabla \cdot D_2\nabla\phi_2^+ - \Sigma_{r_2}\phi_2^+ + \Sigma_{sD_2}\phi_3^+ &= 0\\ \nabla \cdot D_1\nabla\phi_1^+ - \Sigma_{r_1}\phi_1^+ + \Sigma_{sD_1}\phi_2^+ &= 0\end{aligned} \quad (9)$$

If we relabel the quantities in Eqs. 9 according to the following scheme we see that the result is identical with Eqs. 1.

Old label	*New label*
ϕ_3^+	ϕ_1
ϕ_2^+	ϕ_2
ϕ_1^+	ϕ_3
D_3, Σ_{r_3}	D_1, Σ_{r_1}
Σ_{f_3}	Σ_{f_3}
D_2, Σ_{r_2}	D_2, Σ_{r_2}
Σ_{sD_2}	Σ_{sD_1}
D_1, Σ_{r_1}	D_3, Σ_{r_3}
Σ_{sD_1}	Σ_{sD_2}

Thus any machine code that solves Eqs. 1 for the ordinary flux can be used to solve the adjoint equations (Eqs. 9) for the adjoint flux by putting D_3 in the D_1 input, Σ_{r_3} in the Σ_{r_1} input and so on. ϕ_3^+, ϕ_2^+ and ϕ_1^+ will then appear in the ϕ_1, ϕ_2, and ϕ_3 outputs respectively. A check on the results is that the value of ν obtained from solving Eqs. 9 should be the same as that obtained for Eqs. 1.

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Radiation Effects in Quartz—a Bibliography

By R. BECHMANN
U. S. Army Signal Engineering Laboratories, Fort Monmouth, New Jersey

Radiation effects in quartz are significant to our laboratories from two points of view. We want to determine how quartz-crystal oscillators behave in radiation fields and to discover potentially useful effects of radiation on the crystals.

Radiation causes quartz crystals to display changes in color, thermal and electrical conductivity, index of refraction, and elastic properties. We present here a bibliography of literature that describes investigations of these effects. A brief discussion of the effects follows a listing by type. We can class the effects roughly as follows:

a. Early studies (*1–5*)

b. Neutron-induced changes in thermal conductivity (*6–8*)

c. X- and gamma-photon-induced color changes and darkening. References up to 1944 are included in *9*. For more recent work see the references *10* and *12*

d. Color effects from nuclear-reactor irradiation (*13, 14*)

e. Darkening of synthetic quartz by X-rays (*15–18*)

f. Change in optical absorption in natural and synthetic quartz due to X-rays (*16, 19*)

g. Color-center production by X-rays in synthetic quartz (*20–25*)

h. Change in refractive index in natural and synthetic quartz due to X-rays (*26*)

i. Thermoluminescence due to X-rays (*9, 12, 22*)

j. Change in dielectric losses in natural and synthetic quartz due to X-rays (*27*)

k. Frequency change in natural-quartz vibrators due to X-rays (*9, 28–30*)

l. Change in elastic constants due to X-rays (*9*)

m. Change in frequency and frequency-temperature characteristic of synthetic and natural-quartz vibrators due to X-rays and nuclear-reactor radiation (*13, 31*)

n. Change in density and lattice constants of natural quartz due to nuclear-reactor radiation (*13, 32–37*)

o. Annealing (*38, 39*)

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Continued on p. 138

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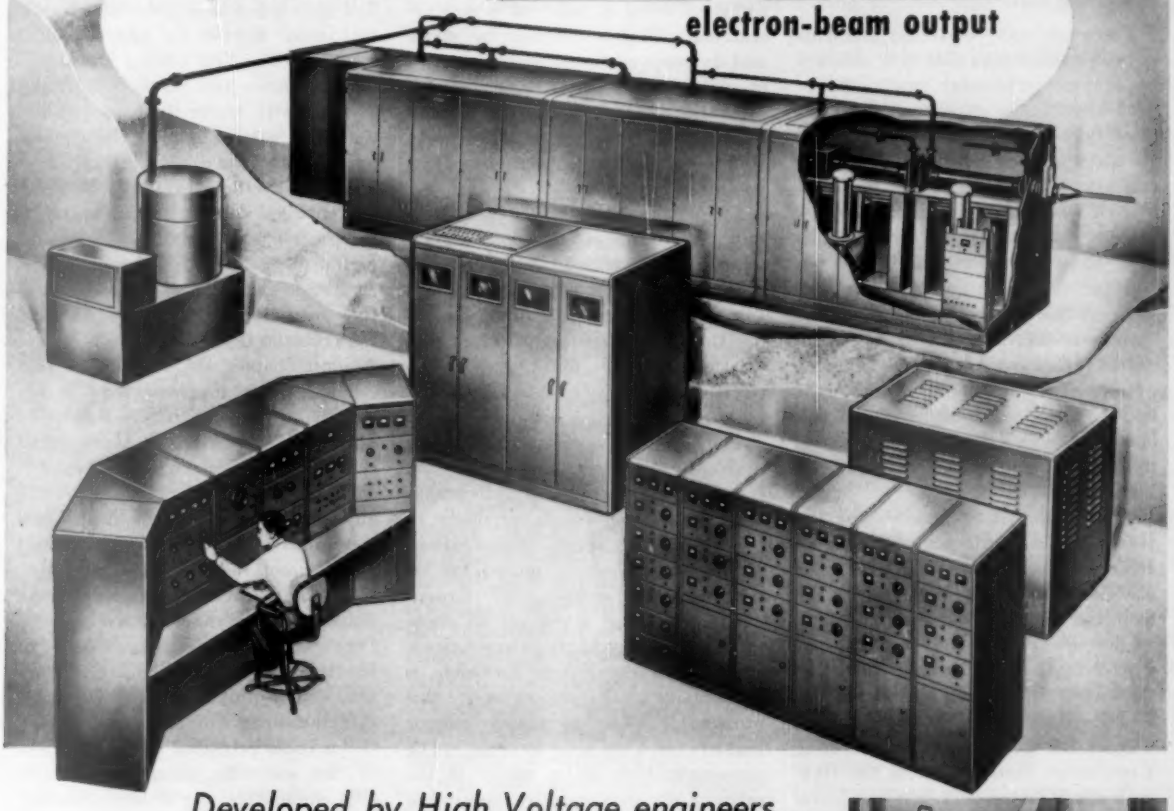

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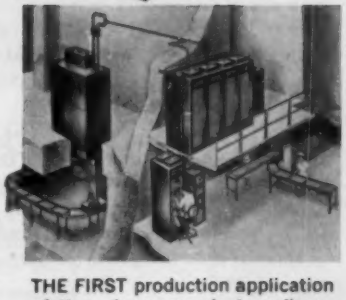

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BOOKS

Corrosion and Wear Handbook for Water Cooled Reactors

Edited by D. J. De PAUL (McGraw-Hill Book Co., New York, 1957, xi + 293 pages, $7.50).

Reviewed by A. A. STRASSER, Nuclear Development Corp. of America, White Plains, New York.

There are many materials problems in equipment design that defy solution by a nonexperimental analytical approach, and even experimental results often defy interpretation. The added variables and restrictions of nuclear reactors make these problems even more difficult to solve than before.

Two conspicuous problems of this type have been corrosion and wear. Reactor designers and builders will welcome this handbook presenting data heretofore unavailable to the general public. As Rear Admiral H. G. Rickover states in the foreword, the book contains "information developed through the expenditure of millions of dollars and thousands of man-years of effort."

The handbook is sponsored by the Naval Reactors Branch, Division of Reactor Development, U. S. AEC. Of the 54 contributing authors, 32 are from the Westinghouse Electric Corp., Atomic Power Division, including the chief editor, D. J. De Paul; 9 of the authors are from the General Electric Co., Knolls Atomic Power Laboratory; 4 from the U. S. Naval Engineering Experiment Station; 3 from the Babcock and Wilcox Co.; 2 from the Naval Research Laboratory; and one each from Argonne National Laboratory, Continental Oil Co., Hall Laboratories and the International Nickel Co.

The book is specifically aimed at the application of materials for PWR types of reactors, the majority of the test procedures and test results being for 500° F pressurized water. A limited amount of data are given for temperatures of 200° and 600° F.

The book is in three parts: the first part discusses fundamentals of corrosion and water technology, the second part discusses testing procedures and test data, the third part discusses specific corrosion and wear problems.

The fundamentals, 25 pages, cover aspects of iron corrosion, friction and wear. A short but valuable chapter on water technology describes the effects of radiation on water and the consequent effects of the products on the corrosion processes.

Considerably more space, 54 pages, is devoted to the description of testing apparatus and testing methods. Static and dynamic test setups are given in sufficient detail to start off a new researcher. This is followed by static and dynamic corrosion and wear data of the various materials tested for pressurized water reactors. Data such as this, presented throughout the Handbook, are the heart of this volume.

Empirical data are difficult to present. The authors have done a good job of it and have defined their terminology well. The effect of variables on corrosion and wear is discussed, including time, temperature, material heat treatment, surface finish, water composition, water velocity and nuclear radiation.

The specific corrosion and wear problems discussed include crevice corrosion, stress corrosion, intergranular corrosion, corrosion products in recirculating systems, considerations of wear and cleaning procedures for nuclear-reactor components. Experimental data are given on all these problems as they apply to pressurized-water reactors. Stress corrosion is particularly well summarized; this problem is likely to plague reactor builders for some time to come. The necessarily high water purity of the primary circuit keeps stress corrosion out of the core, but the presence of impurities in the secondary circuit raises stress-corrosion problems in the heat exchangers. The experimental data presented are new and apparently obtained by the two AEC-owned laboratories operated by Westinghouse and GE.

Isotopic Tracers in Biology, 3rd ed.

By MARTIN D. KAMEN (Academic Press, New York, 1957, xii + 474 pages, $9.50).

Reviewed by EDWARD L. BENNETT, University of California Radiation Laboratory, Berkeley, Calif.

"Isotopic Tracers in Biology" is written as an introduction to tracer methodology as applied to biological research. The book is intended to familiarize the biochemist, physiologist and medical biologist, who may have had little training in nuclear physics and chemistry, with radioactive-tracer methods in their application to biochemical problems.

When the first edition was published in 1947, tracers were just beginning to find application as a powerful research tool in the biochemical and biological sciences. The first edition was a primary reference book for those initiating research with tracer elements. While the third edition follows the general format of the two earlier editions, large portions have been extensively revised and enlarged and brought up to date.

The first two chapters are a general review of nuclear physics and chemistry, while the third chapter discusses the principles, techniques and some of the problems involved in isotope assay. A short chapter on radiation hazards follows. It is supplemented by two related appendices on radioactivity units and standards and the working rules of one radiochemistry laboratory. Together, these three chapters serve as an excellent primer to the health and contamination problems introduced by the use of radioisotopes.

The next short chapter, with the unusual and perhaps disarming title *Practical Interlude*, discusses some of the types of practical and often unanticipated problems that may arise in determining isotopic concentration. Often these problems are not evident in the scientific paper, which usually emphasizes the results obtained. Other theoretical and practical considerations involved in researches with tracers are discussed in the first half of chapter 6. The remainder of this chapter and chapter 7 present informative and stimulating illustrations of the application of tracer methodology to problems of intermediary metabolism. The critical evaluation at the end of chapter 7 of the problem of adequate purification of fractions isolated from biological material when highly radioactive tracers are used is a timely and excellent reminder to those contemplating work with tracers (and also to those who are working with tracers) of the stringent purification problem imposed.

The survey chapter on physiological and medical aspects of tracer methodology has been only slightly revised from the second edition and was the least

interesting and stimulating chapter in the book for this reviewer. The remaining chapters are a survey of the isotopes and radioactive nuclides of importance to biology, with emphasis on the methods of preparation, properties, assay methods and the radiation hazards involved with their use.

A few errors were noted. Alpha (not beta) particles are streams of doubly positively charged helium nuclei (p. 49). On p. 139 it is correctly stated that Cl^{35} in tertiary butyl chloride reacts faster than Cl^{37} with silver nitrate in 98% alcohol. However, the reaction constant for Cl^{35} is 0.7–0.8% greater than that of Cl^{37}, not 0.7–0.8% as great. The ratio of k_{35}/k_{37} is 1.007. The maximum specific activity obtainable with K^{40} is 20 μc/gm K^{40}, not 1 c/gm K^{40} (p. 364). It should also be noted that barium carbonate, which contains 25–40% C^{14}, is now available (p. 140).

"Isotopic Tracers in Biology" is highly recommended study and reading, not only for the neophyte to biological research utilizing tracer methods, but also for those who have had considerable experience with tracer methodology. Although not intended to be a compendium for the expert, it does contain much factual and useful data as well as numerous references. The historical background and description of experiments with which the author is personally familiar contribute substantially to the readability and interest of the book. The quality of printing and binding and the format are up to the usual Academic Press standard.

In the chapter on intergranular corrosion, it was gratifying to note that AISI type 304 stainless steel can be substituted for AISI type 347 stainless steel in 600° F high-purity water with neutral *p*H to a *p*H of 11 without a solution heat treatment to dissolve grain-boundary carbides. Data such as this should correct some of our necessary over-conservatism in design and help economize on materials.

Of importance is the description of fouling of fuel-element heat-transfer surfaces and valve seats. Data presented on wear in high-purity water environment are also valuable and heretofore difficult to find. Suggestions are given on cleaning and maintenance of cleanliness before and during reactor-assembly operations. Although the number of pages devoted to this are few, the importance of these procedures cannot be overemphasized.

This book should become a standard for PWR builders. It is unfortunate that its coverage could not be as broad as its title implies. Water-cooled reactors, such as boiling-water reactors, process reactors and test reactors, are not considered. Excellent corrosion work on aluminum alloys by Argonne National Laboratory, Chalk River and Hanford, for instance, has been omitted. The need for a handbook to cover other types of water-cooled reactors is still unsatisfied.

Progress in Nuclear Energy, Series 8, Vol. 1—The Economics of Nuclear Power

Edited by J. GUERON, J. A. LANE, I. R. MAXWELL and J. R. MENKE (Pergamon Press, Ltd., New York, 1957, xii + 513 pages, $17.00).

Reviewed by RALPH BALENT, Atomics International, Canoga Park, Calif.

This volume is similar in structure to the other works in the "Progress in Nuclear Energy" series. The majority of the content of this volume comes from the information released at the International Conference for the Peaceful Uses of Atomic Energy held at Geneva in August, 1955. In most part, the chapters are direct reprints of the papers given at the Geneva Conference or slightly edited versions of such papers. As might be expected in a field that is expanding and growing as fast as is nuclear power, some of the information, even though only two years old, is already out of date.

The volume covers a broader base than the title implies, as indicated by the five major sections of the volume: "Needs and Resources," "Nuclear Power Economics," "Nuclear Fuel Cycles," "Reactor Programs and Reactor Economic Data," and "Administration and Law." Each of these sections is introduced with a brief resume.

The first section is mostly a collection of summary articles prepared by individual countries on their heat and electrical resources and needs for the next 50 years. These articles were written at the request of the International Commission that prepared the agenda for the Geneva Meeting and were to be used to form a working basis for world energy planning purposes. Since the countries responded differently to this request, the purpose was not completely fulfilled. The articles printed in this section do indicate the great difficulty of long-range predictions and the variety of problems associated with evaluating the data that go to make up such predictions.

The second section covers only 60 pages out of the total 510. The lead chapter in this section, which is entitled *An Evaluation of Geneva and Post-Geneva Nuclear Power Economic Data*, by James A. Lane, collects most of the costs for the various power reactor plants as given at the Geneva Conference. This chapter has since been outdated by Mr. Lane himself with his paper given at the Atomic Industrial Forum in New York City the end of October, 1957, wherein he compares present data to the costs given at Geneva.

The third section, on "Nuclear Fuel Cycles," presents survey articles by W. B. Lewis, J. V. Dunworth and A. M. Weinberg, which are valuable sources of reference material on problems associated with various fuel cycles and possible reactor types utilizing the different fuel cycles. The last chapter, by Spinrad, Carter, and Eggler, contains much valuable reference material on reactivity changes and reactivity lifetimes of fixed-fuel elements in thermal reactors.

The fourth section presents a paper by Sir Christopher Hinton on the Calder-Hall reactor and a summary paper by Staebler on the U. S. Civilian Power Reactor Program. The last chapter in this section, *Reactor Economic Data* by James Lane, could have been combined with the lead article of section three and saved some confusion. The collection of papers in the final section gives the lay reader an indication of the problems associated with administrative and legal aspects of nuclear power.

In summary, the volume is valuable as a reference document but is somewhat expensive for the average worker in the field.

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Annual Review of Nuclear Science, Vol. 7, 1957, edited by J. G. Beckerley (Annual Reviews, Inc., Palo Alto, 1957, viii + 496 pages, $7.00). (*To be reviewed.*)

Progress in Nuclear Physics, Vol. 6, edited by O. R. Frisch (Pergamon Press, New York, 1957, vii + 297 pages, $14.00). (*To be reviewed.*)

Dangerous Properties of Industrial Materials, by N. Irving Sax (Reinhold Publishing Corp., New York, 1957, vii + 1467 pages, $22.50). This handbook is a thorough-going, greatly revised expansion of Sax's earlier "Hand-

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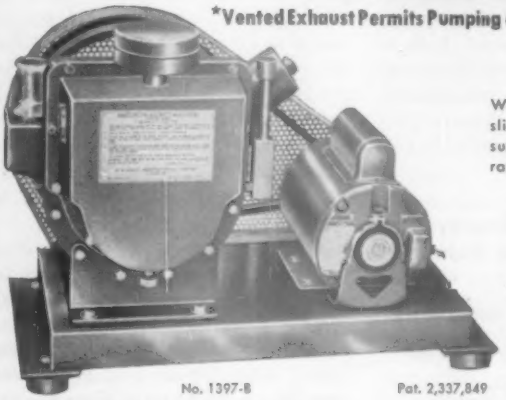

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BOOKS

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book of Dangerous Materials." The bulk of the book (over 1,000 pages) is devoted to the properties of over 8,500 materials, including handling, constants, toxicity and combustion and radiation hazards. In addition, discussions by various experts are provided on specific aspects of handling and personnel protection. Of particular interest in the nuclear field are "Radiation Hazards" by John H. Harley (56 pages) and "Reactor Safeguards" by Joseph J. Fitzgerald (36 pages). Harley's section covers instrumentation rather qualitatively but includes a number of graphs and tables of shielding data plus a tutorial discussion of the industrial and laboratory radiation problems. Fitzgerald's section briefly describes the nuclear reactor field and reproduces "AEC Regulations on Reactor Safety Determination"; the major part of the section is devoted to hazard evaluation rather than to safeguards. Bibliographies are provided for all the sections.

1956 Vacuum Symposium Transactions, Committee on Vacuum Techniques (Pergamon Press, New York, 1957, xi + 234 pages, $12.50). These proceedings contain the papers of the third annual meeting (Oct. '56) of the Committee on Vacuum Techniques. The subjects covered include developments in vacuum technology, instrumentation and applications.

Spectrum of Atomic Hydrogen, by G. W. Series (Oxford University Press, New York, 1958, viii + 88 pages, $2.00). The emphasis of this monograph is on recent work on the structure of the hydrogen atom, i.e., involving the "Lamb shifts" and hyperfine structure. Background material is given on older theories.

Electronic Designers' Handbook, by R. W. Landee, D. C. Davis and A. P. Albrecht (McGraw-Hill Book Co., Inc., New York, 1957, 1152 p., $16.50). Intended to serve as both a text for electrical engineering students and as a practical design guide for practicing engineers, this volume differs from conventional handbooks in that it offers design examples that illustrate the application of the material to specific design problems. Sections of special interest include fundamentals of statistical and probability theory, graphical methods

in the determination of inverse Laplace transforms and design of low-power iron-core transformers and chokes.

An Introduction to Transistor Circuits, by E. H. Cooke-Yarborough (Interscience Publishers Inc., New York, 1957, 154 pages, $2.75). This book is an elementary introduction to transistor theory and applications with emphasis on nonlinear properties of transistors.

Mathematics and Wave Mechanics, by R. H. Atkin (John Wiley & Sons, New York, 1957, xv + 348 pages, $6.00). This text for postgraduate students provides a concise mathematical basis for the study of wave mechanics in its first five chapters. It is written for physics and physical chemistry students.

The Spectroscopy of Flames, by A. G. Gaydon (John Wiley & Sons, New York, 1957, ix + 279 pages, $9.00). This book is intended to replace the author's earlier "Spectroscopy and Combustion Theory." Emphasis is given to recent developments.

Principles of Electrical Measurements, by H. Buckingham and E. M. Price (Philosophical Library, New York, 1957, xxiii + 600 pages, $15.00). Instruments are discussed under the groupings: deflectional, potentiometer and bridge methods; oscillations and vibrations; thermionic tubes; resonance and heterodyne methods; power systems; integrating meters; instrument transformers; and magnetic measurements.

ALSO OF NOTE

Recent Developments in Uranium Milling Technology. This is the transcript of the Mill Technology Symposium and addresses from the annual meeting of the Uranium Institute of America in Denver, May 17–18, 1957. 105 p. *Uranium Institute of America, Uranium Center Building, Grand Junction, Colorado, $5.00.*

Principles of Microradiography. The principles, techniques and applications of X-ray microradiography are discussed. Bibliography gives 500 references. *Instruments Div., Philips Electronics, Inc., 750 S. Fulton Ave., Mount Vernon, N. Y.*

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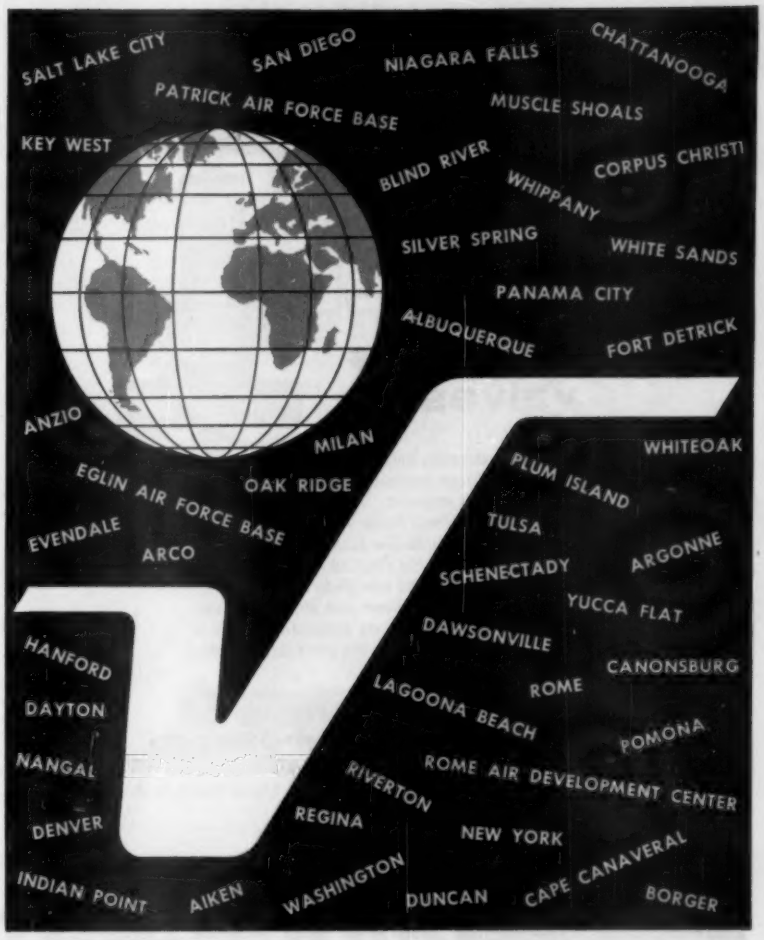

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BOOKS

Department starts on page 124

braries Association, 31 E. 10th St., New York 3, N. Y.

Basic Research—A National Resource. This report by the National Science Foundation provides a statistical and descriptive analysis of the U. S. basic research effort and suggests positive steps that can be taken to stimulate the progress of basic research. 64 p. *Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., 45¢.*

LETTERS

Illustration Credits

DEAR SIR:

At your request we hurriedly sent NUCLEONICS two figures that appeared in your September 1957 issue. We would appreciate it if you would print a correction giving the source of the figures.

The figure on p. 91 taken from report ORNL-2027 (confidential) by J. W. Ullmann. The figure on p. 140 should properly be referenced to "Economics of Waste Disposal" by H. R. Zeitlin, E. D. Arnold and J. W. Ullmann (NUCLEONICS **15**, No. 1, p. 58, 1957).

We certainly enjoyed the issue and congratulate you on assembling such a collection of excellent articles.

—F. L. CULLER, Director
Chemical Technology Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Calibration Aberration

DEAR SIR:

There is an error in our article, "D-C Magnetic Flowmeter for Liquid Sodium Loops" (NU, Oct. '57, p. 122). As we indicated on the proofs, the sentence "It had also been certified by water calibration at Cornell University" refers to the flowmeter, whereas it should refer to the orifices with which the flowmeter was, in turn, calibrated.

—C. G. PFISTER
Knolls Atomic Power Laboratory
and R. J. DUNHAM
General Engineering Laboratory
General Electric Co.
Schenectady, New York

Xenon Oscillations (continued)

This article starts on page 82

age flux, $\bar{\phi}$, while it is actually defined by Eqs. 8. For a sine flux, $\bar{\phi}_1/\bar{\phi}$ is $16/15$ or 1.0667; for a flat flux the two are equal.

• $\bar{x}_1$ was taken as the equilibrium value of x at $\bar{\phi}_1$ to plot a single curve in Fig. 1, while its true value is as defined by Eqs. 8.

The combined effect of this and the first approximation is shown in Fig. 5 which gives a comparison, for piles with a sine flux, between $f(\phi)$ as given in Fig. 1, and the true value, $f(\bar{\phi}_1)$. There is no difference between $f(\phi)$ and $f(\bar{\phi}_1)$ for a flat pile.

• Only the first terms in the expansions for ϕ'' and x'' in Eqs. 7 were used, and consequently the cross terms in Eqs. 8 were neglected.

The effect of all these approximations is zero for a flat flux. For piles with a sinusoidal flux distribution the effect was investigated by solving Eqs. 8 exactly, including two terms in the expansions of Eqs. 7. Since the sine flux shape is symmetrical about the center of the reactor, there is no coupling between even and odd terms in the series of Eqs. 8. For this reason, the two terms were just $(2/H)^{1/2} \sin \pi z/H$ and $(2/H)^{1/2} \sin 3\pi z/H$. The resulting fourth-degree polynomial in ω was solved for several values of the flux; the threshold, at which the real part of ω is zero, was obtained by interpolation.

The flux thresholds were found to be 1.52×10^{13} n/cm² sec for H^2/M^2 equal to 2,500, and 5.0×10^{13} n/cm² sec for H^2/M^2 equal to 1,250. These may be compared with 1.60×10^{13} n/cm² sec and 5.3×10^{13} n/cm² sec shown in Fig. 3. The periods were found to be 29.4 and 22.1 hr, respectively, which may be compared with 29.9 and 22.0 hr shown in Fig. 4. Thus the approximations introduce little error, and a single term in Eqs. 7 and 8 is adequate.

* * *

The information contained in this report was developed during the course of work under contract AT(07-2)-1 with the AEC, whose permission to publish is gratefully acknowledged.

BIBLIOGRAPHY

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2. A. F. Henry and J. D. Germann, Oscillations in the power distribution within a reactor, *Nu. Sci. and Eng.* **2**, No. 4, 469 (1956)

1948 — ORGANIZATION OF BETTIS ATOMIC POWER DIVISION
1953 — DEVELOPED: FIRST NUCLEAR PROPULSION UNIT
1955 — BUILT: REACTOR FOR FIRST NUCLEAR SUBMARINE
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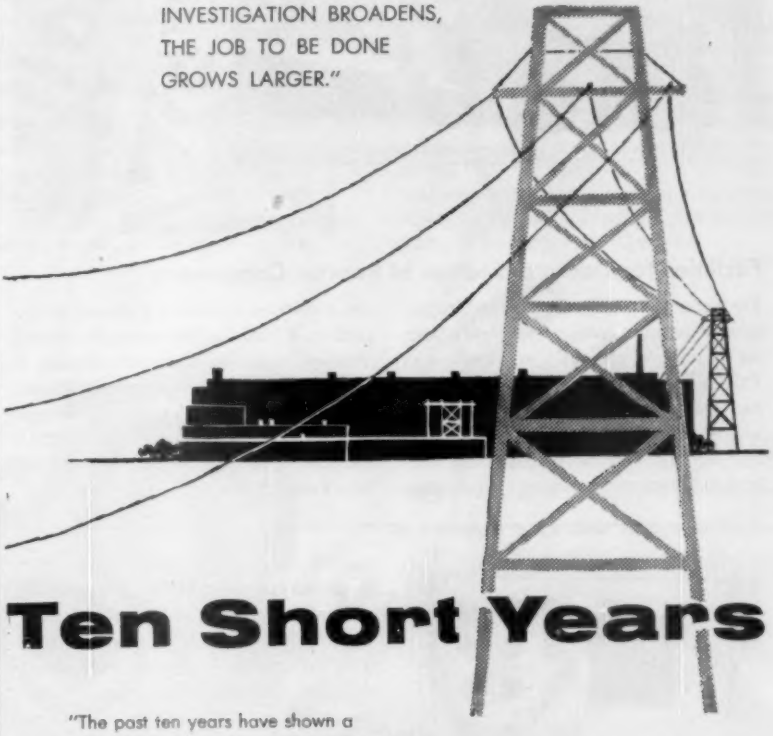
TODAY—"AS WE LOOK TO THE FUTURE OF NUCLEAR POWER IT IS EVIDENT THAT WE ARE STILL FAR FROM OUR ULTIMATE GOAL OF TOTAL DEVELOPMENT... AND WITH EACH NEW DISCOVERY OUR AREA OF INVESTIGATION BROADENS, THE JOB TO BE DONE GROWS LARGER."



Ten Short Years

"The past ten years have shown a tremendous advance in nuclear technology, yet every step forward reveals a still broader view of the future and one realizes that the next ten years will show an even greater acceleration in the development of this new power source. In short, to date we have done little more than make a good beginning.

The young men who enter this field today will have the responsibility of creating a solid structure of knowledge and accomplishment from this beginning. Yet, even they, ten years from now, will look ahead and know they are still far from fully realizing the ultimate potential of nuclear energy."

You can participate in the continuing development of this expanding field of activity. A field whose only limits are the creativity of man's mind and the extent of his desire to learn. If you are a U.S. Citizen with an advanced degree in Physics, Mathematics, Metallurgy, or Engineering, and would like to apply your knowledge to the field of nuclear power, send your resume to: Mr. M. J. Downey, Dept. #A-30, Bettis Atomic Power Division, Westinghouse Electric Corp., P.O. Box 1468, Pittsburgh 30, Pa.

BETTIS ATOMIC POWER DIVISION
Westinghouse
BETTER YOUR FUTURE AT BETTIS

Facilities for Decontamination of Reactor Components

Facilities for radioactive decontamination of reactor components have been set up and are presently in operation at Fairchild. Apparatus that can be decontaminated in the facility include valves, pumps, small heat exchangers and tubing, turbine blading and control-rod drive mechanisms. For example, a control-rod drive is shown above getting a bath in the specially mixed chemical solution that will cleanse it of radioactivity. Equipment is also available for refurbishing the decontaminated components.—Fairchild Camera and Instrument Corp., Robbins Lane, Syosset, N. Y.

Strain Gage Indicator

Indicator (above) accepts inputs from resistance-type transducers via a null balance servo and converts these analog signals to digital readout in true units of measurement. The panel permits adjustment of controls to accommodate full- or half-bridge transducers with 1, 2 or 4 active legs, and to select the proper polarity. A choice of visual or automatic digital readout is available to indicate and record the measured values on printers, electric typewriters, paper tape perforators and IBM punch card devices.—Datran Electronics Div., Mid-Continent Mfg., Inc., 3615 Aviation Blvd., Manhattan Beach, Calif.

Alumina Ceramics

Alumina Ceramics, produced in a variety of sizes and geometries either in prototype or production quantities, offer neutron cross section of <1 barn, no structural change after exposure to 2×10^{20} n/cm^2, good chemical resistance, thermal stability and electrical insulation, and can be metallized and brazed to stainless steels or other metals to form a hermetic seal.—Frenchtown Porcelain Co., Frenchtown, N. J.

Ferro Columbium

Reactor-grade ferro columbium has a columbium-to-tantalum ratio of about 40 to 1. The 0.8% tantalum content of this material will assure that columbium-containing cast (ACI type CF-8C) and wrought (AISI type 347) stainless reactor parts are well within the AEC specification of 0.10% maximum tantalum content. Percentages of other elements are: columbium, 65%; silicon, 0.10%; and carbon, 0.02%.—Shieldalloy Corp., Newfield, N. J.

Scintillation Detector

Model P-20C, recent modification of a standard scintillation detector, incorporates a by-pass switch on its back plate to permit photomultiplier output pulses to by-pass the built-in stable pulse amplifier so as to feed directly a linear amplifier for spectrometry work. Nine different crystal and adapter combinations can be attached to the base unit.—Tracerlab, Inc., 1601 Trapelo Rd., Waltham 54, Mass.

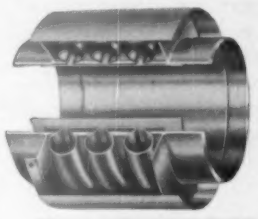
Reducing Flanges

Tapered Fluoroflex-T reducing flanges are lined with a virgin Teflon compound. The full face of the flange, with its asbestos backing, is an integral part of the liner, thus providing high-corrosion protection and chemical inertness. The flow passage is tapered to minimize turbulence and the reducers withstand 150 psi and full vacuum at $-100°$–$500°$ F. The flanges are available in 1–5-in. ASA pipe sizes.—Resistoflex Corp., Roseland, N. J.

Air Monitor

Model AM-33 (above) makes possible the simultaneous measurement of both alpha and beta-gamma activity of airborne particulates with a single instrument. It combines in one integrated unit a detector, amplifier, discriminator, anticoincident circuit, counting ratemeter, high- and low-voltage power supply, alarm system and continuous

NEW ZALLEA HyPTor* TOROIDAL EXPANSION JOINT



HyPTor corrugations have a circular or toroidal cross section which provides a lower operating stress at any given pressure than any other corrugation shape.

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This unique toroidal expansion joint with thin-walled bellows is setting new performance and durability records in high pressure, high temperature service. It was developed to meet the severest operating conditions without sacrificing long life.

Minimum stress at high pressures is one advantage of the Zallea HyPTor. This is due to the thin-walled bellows and toroidal corrugations. Thin walls develop lowest flexing stress. The toroidal cross section assures lower operating stress at any pressure.

Superior performance at high temperatures. The toroidal corrugation of the HyPTor makes it suitable for use at high temperatures. Also, the HyPTor is hydraulically formed and free from circumferential welds which would act as stress raisers.

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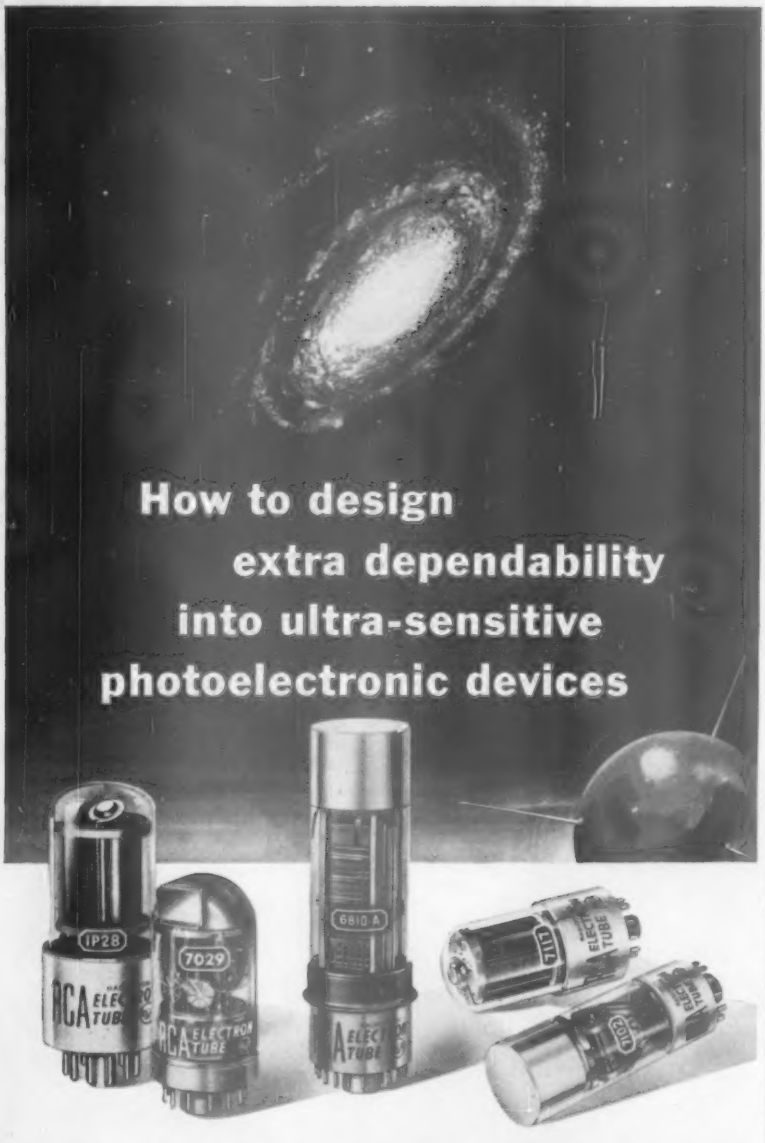

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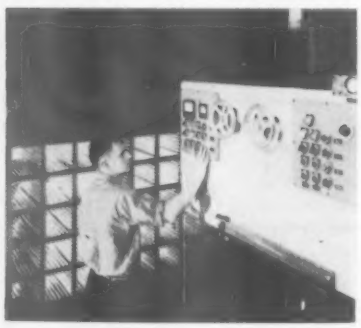
Electron Tube Division Harrison, N.J.

For data on specific RCA Multiplier Phototubes, write RCA Commercial Engineering, Section C-31-U, Harrison, New Jersey.

PRODUCTS & MATERIALS

Department starts on page 130

recording unit. The basic detector is a gas-flow proportional counter with a thin Mylar window. Operation is automatic and continuous without attendance for periods up to one month.—Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis 18, Ind.

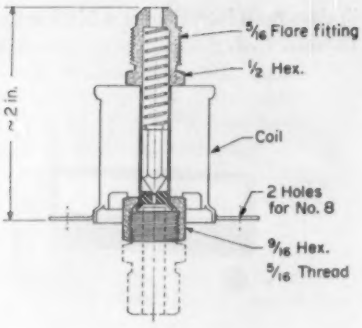


Deep Hole Driller

Deep hole driller (above), on its initial effort, repeatedly thrust a $1\frac{3}{16}$-in. drill through 18 in. of 347 stainless steel to remove 6-in. squares with speed and accuracy. With this method, costly material was salvaged, and, even more important, there resulted a considerable savings of time and elimination of work on the next operation. The manufacturer maintains a dual operation selling both machine tools and services.—Canton Tool Mfg. Co., East Canton, Ohio.

Log N Micromicroammeter

Model 413 (above) reads from 10^{-11} to 10^{-5} amp without range switching. Both input and output are at ground. Polarizing potential (+216 v) is furnished at back of chassis. Other features include: zero drift less than 0.05 decade in 24 hr after 1-hr warmup, accuracy within 0.02 decade, output of 0 at 10^{-11} amp rising to −50 mv at 10^{-5} amp and output noise less than 1% of full-scale reading.—Keithley Instruments, Inc., 12415 Euclid Ave., Cleveland 6, Ohio.

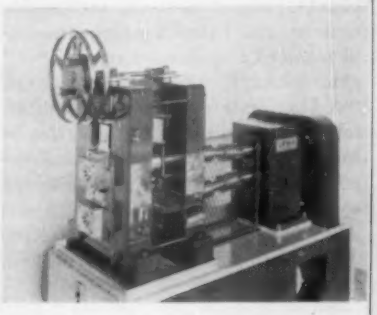


Solenoid Valve

Solenoid valve (above) for use on air, water or oil differs from conventional models in that the flow is straight through the solenoid armature housing. The miniature valve, measuring about 2 in. over-all, is resistant to moisture and suitable for use with corrosive materials. Several models are available with monel and stainless-steel parts. Solenoids in all models are encapsulated in epoxy resing. A variety of end fittings also are available to meet specific needs.—Fulton Sylphon Div., Robertshaw-Fulton Controls Co., P. O. Box 400, Knoxville 1, Tenn.

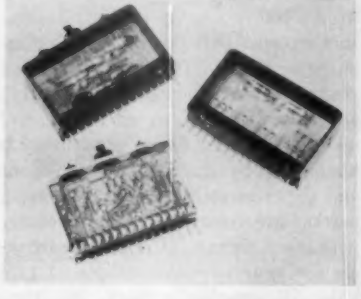
Leak Detection System

The Radiflo (above) is a supersensitive, nondestructive, leak-detection system for quality control and testing of hermetically sealed containers. Using the nontoxic, radioactive gas Radene III at a pressure greater than the internal pressure of the sealed units or test samples, leakages as small as 10^{-12} standard cm^3 of air per second can be accurately determined. Normally prepared and shipped in high concentration to reduce the weight of required shielding, Radene III can be diluted with any desirable gas—dry air, nitrogen, etc.—and the dilution factor adjusted for varying sensitivity test requirements.—Reed-Curtis Nuclear Div., American Electronics, Inc., Culver City, Calif.



Laboratory Rolling Mill

Designed to take the heavy pass reductions and to maintain the close thickness tolerances required in the processing of such materials as high-temperature alloys, stainless steels and refractory metals, the heavy-duty, high-precision, combination rolling mill (above) has high separating force and torque transmission capacities. It is currently available with 6–15-in. back-up-roll diameters, ¾–5-in. work roll diameters and face widths up to 24 in. Depending on size and application, the mill is furnished with needle-roller or oil-film sleeve bearings on the journals, with manual or twin-motor screw-down and with either constant-speed a-c or variable-speed d-c drives.—Loma Machine Mfg. Co., Inc., 114 E. 32nd St., New York 16, N. Y.



Computer Building Blocks

Transistorized logical building-block packages (above) make it possible to jump from symbolic logic or Boolean algebra to finished equipment without an intermediate electronic-development stage. Ordinarily room-size computers can be designed to desk dimensions with the building blocks. No air

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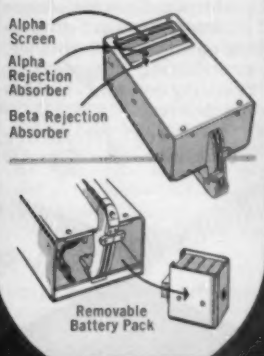
Juno is a portable, battery-operated instrument which measures the intensity of, and distinguishes between alpha, beta, and gamma radiation. Available in two models, with 3 ranges each: SRJ-6 (standard range) 50, 500, and 5000 MR/HR; HRJ-6 (high range) 250, 2500, and 25,000 MR/HR.



TECHNICAL ASSOCIATES

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Frenchtown alumina ceramics are produced in a variety of sizes and geometries, either in prototype or production quantities. Dense shapes of over 200 cubic inches have been manufactured.

To engineers and scientists who wish to learn more about the capabilities and limitations of alumina ceramics, Frenchtown welcomes the opportunity to assist in the selection and proper utilization of these amazing materials. This assistance is directed toward obtaining optimum performance, simplifying complexity, reducing cost and expediting delivery.

Technical literature will be sent upon request.

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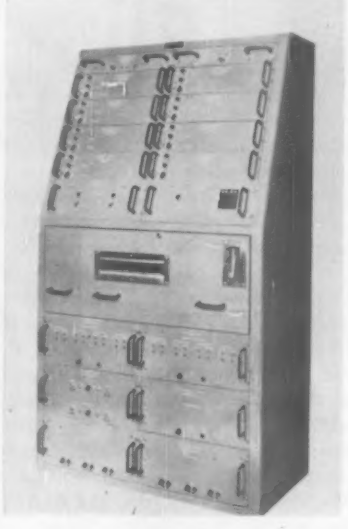
conditioning is needed, and each logical element occupies only 2½ cubic inches. The eight basic building blocks are the bistable trigger element, monostable element, gated amplifier element, complementer amplifier element, "or" gate package, "and" gate package, "and-or" gate package, and emitter-follower package. When operating at temperatures above 25° C, some derating of load current and switching speed is necessary.—Research and Advanced Development Div., Avco Mfg. Corp., 20 South Union St., Lawrence, Mass.

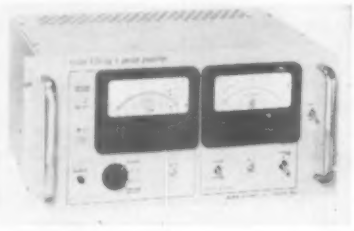


Recorder

Model 260 (above) is an instrumentation recorder that presents instantaneously up to eight 11-in. scale traces on electrosensitive paper to within 1% accuracy with a transient response of up to 3,000 cps. Recorder accuracy is unaffected by line voltage variations and paper stretch because calibration marks are recorded simultaneously with input signals. Coordinate markers are generated internally and provide 5% amplitude lines and time markers at 1, 0.1, or 0.0167 sec intervals. —Consolidated Avionics Corp., Westbuy, N. Y.

Cast Stainless Fittings

Complete line of cast stainless-steel fittings designed for service to 2,500 psi at 670° F are available in both the 300 and 400 alloy series stainless steel in sizes 8–30 in.—Cooper Alloy Corp., Hillside, N. J.

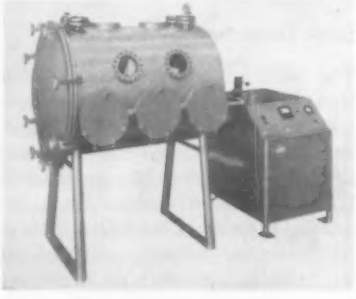


Log N and Period Amplifier

Model 420 (above) combines a logarithmic micromicroammeter and a reactor period meter. It measures current from 10^{-13} to 10^{-16} amps and positive or negative reactor period of 3–30 sec. After warmup, drift of the log circuit is within 0.05 decade in 24 hr. The period meter has 5-sec recovery time from overload and adjustable response time over a 10–1 range. Other features are: large full-scale outputs to drive remote meters, 50-mv outputs for recorders, a regulated 225-v polarizing potential for ion chambers and simplified operating and calibration controls.—Keithley Instruments, Inc., 12415 Euclid Ave., Cleveland 6, Ohio.

Powdered-Titanium Parts

Compacted and sintered titanium-powder parts that cover a wide range of types and sizes are offered with the following physical characteristics: apparent density, 4.20 gm/cm^3 (4.54 gm/cm^3 theoretical); ultimate tensile, 65,000 psi; elongation, 10%; yield point in compression (0.2% offset), 55,000 psi; Rockwell hardness, A-50.—Keystone Carbon Company, St. Marys, Pa.



Packaged Welding System

Model 6-10 (above) is a completely-integrated controlled-atmosphere weld-

ing system designed for metallurgical research. It occupies a floor area of 5 × 8 ft and stands 6 ft high. The welding chamber is 3 ft in diameter and 4 ft long. Six glove, two light, and four viewing ports are provided. All the controls are on the accompanying pumping console. The new device pumps down to 5×10^{-3} mm of Hg in ~15 min with a guaranteed maximum leak rate of 50 μ/hr.—L & B Welding Equipment, Inc., 2424 Sixth St., Berkeley, Calif.

Magnetic Switching Reactors

Standard line power magnetic switching reactors (above) are offered in four nominal ratings of 15, 75, 150 and 300 volt-amperes. These units translate inputs to plain logic then perform switching operations for either a-c or d-c loads, depending on circuit arrangement. No special power supply is required and they are compatible with other switching reactors. Units range in size from 3⅝ × 3 × 2¼ in. (15 va) to 5¼ × 5¼ × 4½ in. (300 va).—Control Div., Magnetics, Inc., Butler, Pa.

Metallic-Fire Extinguisher

X-8, developed for extinguishing metallic fires by shoveling or pouring directly onto burning parts, ingots or scrap piles, can be used as a packing material or as an additive to zirconium scrap piles to prevent spontaneous combustion. X-8 contains no borates or other fusible salts and, therefore, is less likely to contaminate these metals.—Mercantile Metals, Inc., P. O. Box 478, Carnegie, Pa.

Lead-Filled Resin

Maraset 341 is a lead-filled epoxy casting material for radiation shields. Available in lead concentrations up to 95 wt % and densities up to 7.9 gm/cm³, it is easily cast in inexpensive molds. Curing takes place overnight at room temperatures. Cast material is rigid and bonds well to glass, wood, metal and ceramics.—Marblette Corp., 37–31 Thirtieth St., Long Island City 1, N. Y.

Teflon Bellows

Molded Teflon bellows have twice the burst strength and 20 times or more the flex life of conventional bellows machined from Teflon cylinders. Fluoroflex-T molded bellows cover both low- and medium-pressure service with dynamic working pressures as high as 120 psi, bending deflection up to 70 deg and axial movement to 2 in. or greater. They withstand temperatures as high as 450° F and are completely unaffected by all chemicals except molten alkali metals and fluorine at elevated temperatures and pressures.—Resistoflex Corp., Roseland, N. J.

Titanium Pipe Fittings

New line of titanium fittings for nuclear chemical-processing piping systems offers savings in weight, with greatly increased resistance to corrosion and erosion plus stability at elevated temperatures. Fittings made of titanium are practically impervious to attack by corrosive salts at moderate temperatures. Titanium fittings provide wide latitude in tensile strength, fatigue resistance and ductility under a wide range of conditions.—Ladish Co., Cudahy, Wis.

Pulse-Height Analyzer and Scaler

Model 132 Analyzer Computer (above), designed for use with all gamma-sensitive scintillation counters, combines a 500–1,500-v regulated supply, single-channel pulse-height analyzer, binary scaler and an automatic push-button computing circuit. Window width is 0–10 v and is independent of 0–100-v base-level setting to within 2% from 5 to 100 v. Repeat preset time accuracy is 0.04 sec. The preset count circuit

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PRODUCTS & MATERIALS

Department starts on page 130

permits selection of any one of eight different predetermined counts from 400 to 51,200 total counts.—Nuclear-Chicago Corp., 229 W. Erie St., Chicago 10, Ill.

Seamless Tubing

Mandrel-drawn, seamless, stainless-steel tubing gives a freer flow and a higher degree of corrosion resistance than ordinary rod-drawn tubing. Called Lustraloy, the tubing is available in sizes from ⅜- to 1½-in. o.d. and 0.020–0.109-in. wall thickness.—Columbia Steel & Shafting Co., Carnegie, Pa.

Nitrogen-15 Compounds

Offered are four new compounds of Nitrogen-15 in two forms—a standard compound (7% N^{15}) and an enriched compound (25% N^{15}). The four new compounds are 60% nitric acid (HNO_3), ammonium nitrate, (NH_4NO_3) potassium nitrate (KNO_3) and ammonium sulfate $(NH_4)_2SO_4$.—Tracerlab, Inc., 1601 Trapelo Rd., Waltham, Mass.

Floor Surfacing

Poly Rock FG-777 is an industrial floor surfacing composed of blended air-cured resin with special types of Fiberglas reinforcing. Acid-and water-resistant, it is applied by brush and trowel over concrete or wood, in or out of doors, taking an hour to harden and six hours to cure. It is available in two shades of gray; special colors can be provided on request.—Plant Maintenance, Inc., 623 Green Road, Cleveland 21, Ohio.

LITERATURE AVAILABLE

Electronic instruments described briefly in a new short form catalog. Included are the following: Model CL 100 accelerator current integrator, Model PH-200 universal photomultiplier, Model TH-300 millimicrosecond time-to-pulse-height converter, and Model PA-400 multichannel pulse-height analyzer.—Eldorado Electronics Co., 2821 Tenth St., Berkeley, Calif.

Carbon-14 labeled compounds given new price list (1057) that contains an increased selection of compounds, particularly the purines and pyrimidines.—Research Specialties Co., 2005 Hopkins St., Berkeley 7, California.

Thermal elements discussed with regard to the selection of those with maximum resistance to corrosive atmospheres in 4 p. Bulletin 110.—The Partlow Corp., 505 Campion Road, New Hartford, N. Y.

Industrial periscopes, their design and use for remote viewing, covered in 4 p. bulletin.—Kollmorgen Optical Corp., 347 King St., Northampton, Mass.

Pipe fittings for nuclear and conventional power installations illustrated and described in General Catalog 55.—The Ladish Co., Cudahy, Wisc.

Temperature control equipment for stress-rupture and creep testing are discussed in 2-page data sheet.—Leeds & Northrup Company, 4934 Stenton Ave., Philadelphia 44, Pa.

Bistable diode, recommended for application in bistable circuits, ring counters and various switching functions, is discussed with diagrams, in a 4-page folder.—The Shockley Semiconductor Laboratory, Beckman Instruments, Inc., Mountain View, Calif.

High-frequency induction units and accessories for rapid high-temperature combustion of laboratory samples described in bulletin, T-1067. 12 p.—Laboratory Equipment Division, Lindberg Engineering Co., 2444 W. Hubbard St., Chicago 12, Illinois.

Sample-counting equipment, described with emphasis on selection and including a comparative summary of the cost of all instruments covered, is the subject of Bulletin 89.—Tracerlab, Inc., 1601 Trapelo Road, Waltham 54, Mass.

"The Atomic Revolution" is the title of picture-caption booklet that explains the theory and peaceful uses of nuclear fission and fusion for high school and college students.—General Dynamics Corp., 445 Park Ave., New York 22, N. Y.

Thermocouple general application data, covering thermocouple elements, protecting tubes, thermocouple extension wire and thermocouple insulators, is described in several folders.—Claud S. Gordon Co., Chicago, Ill.

Protective coatings of synthetic resin, corrosion and solvent resistant, are described in new bulletin along with typical applications. 12 p.—Mono-Seal

Products, 44 Garden Street, Everett 49, Mass.

Boron isotopes of masses 10 and 11, with information regarding their physical, chemical and nuclear properties and the availability of boron and its compounds are discussed in booklet. 10 p.—Hooker Electrochemical Co., Niagara Falls, New York.

Radioactivity detection and analysis provided by Baird-Atomic 1958 nuclear instruments described in detail in Catalog A-1.—Baird-Atomic, Inc., 33 University Rd., Cambridge 38, Mass.

Carbon-14 labeled compounds and prices are listed in Technical Bulletin N-18.—Nucleonic Corp. of America, 196 Degraw St., Brooklyn 31, N. Y.

"Electronic Instruments for Nuclear Science" is title of 28-p. Catalog 58 containing detailed descriptions of spectrometers, scalers, counters, etc.—Tullamore Electronics Laboratory, 6055 S. Ashland Ave., Chicago 36, Ill.

Transistorized beta-gamma monitors are described in 4-p brochure.—Universal Atomics Div., Universal Transistor Products Corp., 36 Sylvester St., Westbury, L. I., N. Y.

Ionization gage that reads in the 10^{-12} mm Hg region is subject of Bulletin P9-10.—Consolidated Electrodynamics Corp., 1775 Mt. Read Blvd., Rochester 3, N. Y.

Stainless-steel fastener selector and stock list comprise 8-p guide.—Allmetal Screw Products Co., Inc., 821 Stewart Ave., Garden City, L. I., N. Y.

"Filters for Nuclear Applications" is title of 4-p folder.—Purolator Products, Inc., 970 New Brunswick Ave., Rahway, N. J.

Uses of stainless steel in the nuclear field is subject of 4-p bulletin.—Alloy Tube Div., The Carpenter Steel Co., Union, N. J.

Metal-processing machines that can be used in the fabrication of fuel elements are described in Publication 1057. 16 p.—Stanat Manufacturing Co., 500 Shames Dr., Westbury, L. I., N. Y.

Oscillographic recording equipment is described in 16-p catalog.—Industrial Div., Sanborn Co., 175 Wyman St., Waltham 54, Mass.

Health physics is discussed in all its phases in Pamphlet TL-88.—Tracerlab, Inc., 1601 Trapelo Rd., Waltham 54, Mass.

"Instrument and Control Switches" is the title of 8-p Bulletin 14B8112A.—Allis-Chalmers Manufacturing Co., Milwaukee 1, Wisc.

"Atomlight" is the title of a new bimonthly bulletin containing short technical articles on tracer applications. Sample subject: tritium labeling.—New England Nuclear Corp., 575 Albany St., Boston, Mass.

Regulator valves available in monel and aluminum for corrosive services are described in 32-p catalog.—Jordan Industrial Sales Div., OPW Corp., 6013 Wiehe Rd., Cincinnati 13, Ohio.

Liquid scintillation spectrometers for counting tritium and C^{14} samples is the subject of 4-p Specification 314-8-57.—Packard Instrument Co., Inc., P. O. Box 428, La Grange, Ill.

INDUSTRY NOTES

Tracerlab-Keleket, Inc. has moved the **Keleket International Corp.** from New York to the corporation headquarters in Waltham, Mass.

Structural Display Co., Inc. of L.I.C. designs and produces displays exhibiting applications of atomic energy. The companies represented through its projects at the "Atomfair" in the New York Coliseum last October were the **Shell Oil Co., ACF Industries, Inc.** and the **Budd Co.**

Eldorado Electronics, manufacturer of nuclear electronic instruments, has moved from Oakland to larger leased quarters in Berkeley, Calif.

The Federal Civil Defense Administration, Battle Creek, Michigan, has approved and ordered into production a transistorized dosimeter charger for civil defense that is manufactured by **Universal Transistor Products Corp.,** Westbury, N. Y.

Hamner Electronics Co., Inc., of Princeton, N. J. has appointed **Crossley Associates, Inc.,** manufacturers representatives of Chicago, Illinois, to handle its line of nuclear and electronic instruments.

Walter Kidde Nuclear Laboratories is performing a radiological survey of soil, water, air and biological conditions in the vicinity of the **Industrial Reactor Laboratories** research reactor being built by **AMF Atomics** near Plainsboro, N. J.

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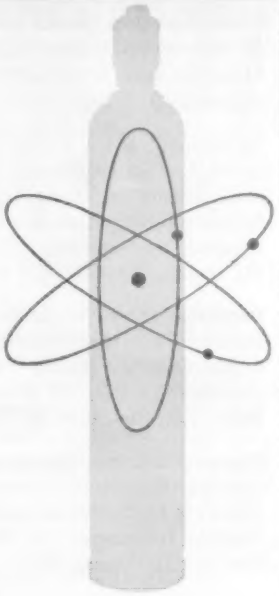

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Quartz Bibliography

Continued from p. 122

atoms by fast neutrons (*7, 32, 33, 40–47*)

Color Effects

Unirradiated high-grade quartz is clear and uncolored. With several hours of X irradiation, natural quartz becomes a uniform gray.

The susceptibility of synthetic quartz to darkening under X irradiation is related to impurity content. Synthetic quartz grown in the presence of aluminum darkens readily. Aluminum atoms, probably incorporated substitutionally, become optical centers upon ionization (*19*).

Pile-irradiation darkening is very similar to photon darkening in both pattern and intensity. Darkening increases up to neutron exposures of 6×10^{16} nvt. Thereafter steady bleaching takes place to $\sim 3 \times 10^{18}$ nvt when the crystals are transparent and clear again (*13*). Heat treatment generally anneals color changes.

Frequency Changes

Irradiation causes an exponential frequency change toward a saturation that can be as much as 0.02% for photon irradiation and 1.4% for neutron irradiation. Suitable heat treatment almost completely anneals the frequency changes (*13*).

The exponential change varies in rate and magnitude with cut, initial frequency and thickness, and previous history (*9*). Amount of change appears to be related to extent of blackening. The greatest changes are limited by cessation of oscillation at high neutron exposures (*13*).

It is found that half of the X-ray saturation change (0.018%) for a certain type of plate is produced by the following doses:

Radiation	*Dose (rad)*	*Temperature (°C)*
X-rays	14.4×10^6	20
Reactor	4.8×10^6	95

Mechanical Properties

Fast-neutron-irradiated quartz exhibits an anisotropic increase in volume and a decrease in density in three stages: The first is a slow change apparently indicating displacement of atoms into available interstitial positions; the second is a more rapid change of magnitude indicating further atomic displacements; finally at exposures of $\sim 10^{20}$ nvt single-crystal X-ray reflections disappear (*33*).

NEWSMAKERS

University of California Radiation Laboratory at Livermore has appointed its fourth and fifth associate directors, **Harold Brown** and **John Stuart Foster, Jr.** CRL director is Herbert York.

Carter L. Burgess has taken over the presidency at American Machine & Foundry, succeeding Morehead Patterson, board chairman. Patterson held both jobs until Burgess, an industry and university executive, came to AMF. Burgess is a former assistant secretary of defense and former president of Trans World Airlines.

Dr. Frank C. Hoyt, physics chief at Lockheed Missile Systems division, has been named to AEC's committee of senior reviewers. The committee has scheduled a thorough study of AEC's weapons classification policy.

GE's Vallecitos Atomic Laboratory has promoted **Samuel Untermyer II,** designer of VBWR, to be consulting engineer on reactor technology, following successful initial operation of the boiling reactor. **Edward P. Lee** was named reactor operations manager.

J. Emmett Maider and **O. B. Falls, Jr.,** have been named to new posts in General Electric's Atomic Power Equipment Dept. Maider, manager of the Dresden project until appointment as manager of project operations for APED in 1956, will head a new, combined section on marketing and projects. Falls, former APED marketing manager, will serve as consultant to **George White,** general manager of the department.

B. John Garrick has joined Holmes & Narver, Inc., Los Angeles, as chief nuclear scientist in the firm's new nuclear division.

Burns & Roe, Inc., has picked **William G. Carlson** to handle preliminary design of supporting facilities for AEC's plutonium reactor project at Hanford, Wash. Carlson developed the Burns & Roe design for nuclear aircraft engine test facilities at AEC's Idaho reactor test station.

Dr. James H. Klein has been given major responsibility for expansion of Stanley Aviation's technical capability in the missile and nuclear power fields. He joined the company as chief research engineer after 18 months of work on missiles and reactors at Ramo-Wooldridge Corp.

Bendix Aviation has elevated **Murray Kanes,** electromechanical development chief, to general manager, Friez Instrument div. Kanes directed early development work at Oak Ridge on nuclear propulsion for aircraft.

John A. Harris, Jr., of the Associated Press Washington bureau, has succeeded **Robert Solomons** as information officer at AEC's Oak Ridge Operations Office. Solomons was recently named nuclear information officer for the state of Kentucky.

Atomics International has sent its top reactor man, **Frank E. Faris,** to Germany to take on management of the technical dept. of Interatom, new joint subsidiary of AI and Demag AG, Duisburg (NU, Jan '58, 19). Demag has contributed **Lars C. Fischer-Zernin** to Interatom to handle sales. Faris directed development of two AI reactors for AEC—the sodium experiment near Los Angeles and the organic moderated experiment at Idaho Falls. **Marlin E. Remley** has taken over as acting chief of AI reactor development.

Faris

Alan R. Gruber, formerly of Nuclear Development Corporation of America, (NDA) has been named assistant chief engineer in charge of nuclear systems research for Marquardt Aircraft's long-range planning & research division. The division has been dubbed "Astro," for the initials of air-space travel research organization.

The American Institute of Mining, Metallurgical and Petroleum Engineers has bestowed its highest award—honorary membership—upon **Donald Hamilton McLaughlin,** president of Homestake Mining Co.

Kaiser Engineers Division of Henry J. Kaiser Co. has a new assistant general manager—**J. E. Hughes,** former vice president of the parent firm. He will

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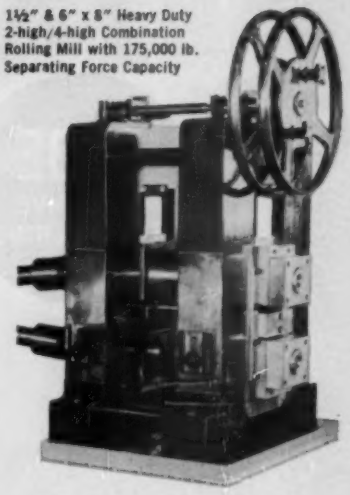

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NEWSMAKERS

Department starts on page 139

be responsible for all Kaiser design, engineering and construction services to the steel, petroleum, nuclear, chemical, power and minerals industries.

Frank E. Myers and **Joseph M. Harrer** have been appointed associate laboratory director and associate director of reactor engineering, respectively, at Argonne National Laboratory. Myers was granted a 2-year leave of absence from his posts as dean of the graduate school and head of the physics dept. at Lehigh Univ. His job at ANL, a new one, gives him guidance of ANL's program to train more nuclear scientists and engineers. Harrer, a 10-year man at ANL, will continue to direct the lab's work on boiling water reactors.

Myers

Harrer

Appointment of **Harold Sowman** as supervisor of materials, nuclear research section, has been announced by Minnesota Mining & Manufacturing.

Donald J. McPherson has been appointed manager for metals research at Armour Research Foundation, Illinois Institute of Technology. He will direct all research in reactor metallurgy.

Isotope Developments, a British firm, has filled two top posts in its engineering make-up: **R. Y. Parry,** technical manager, and **J. S. Eppstein,** chief engineer.

Phillip Thompson of Nuclear Metals, Inc., has been named to serve on the Massachusetts Commission on Atomic Energy.

Tracerlab, Inc., has filled two top posts. **Gen. Russell L. Maxwell** has been added to the Washington staff for consultant-liaison work with the government; **Everett Sarratt** has been named chief engineer for instrument products responsible for development of all nuclear laboratory equipment. The addition of Gen. Maxwell was explained as part of Tracerlab's first real effort to get government business.

NUCLEAR CAMPUS

• AEC grants of $81,106 to Case Institute of Technology will permit the Cleveland school to expand both its physics and chemistry programs in nuclear science. They will buy geiger counters, scintillation counters, ionization chambers and other nuclear equipment, add four new courses in nuclear chemistry and purchase a heat transfer loop and a solvent extractor.

• A proposal for a state-sponsored nuclear college, to be located near AEC's Hanford Works at Richland, Wash., has been gaining ground since the first of the year. The state's advisory council on commerce and economic development took its first look at the proposal in January and has scheduled a full study this year. The school might be a unit of either the University of Washington or Washington State College, or a joint enterprise of both.

• AEC and New York Univ. have cemented a working research-teaching arrangement between the former's Health and Safety Laboratory at the New York Operations Office and the latter's Institute of Industrial Medicine (co-sponsored by Bellevue Medical Center). Members of the HASL staff will serve on the Institute's faculty, and Institute personnel will work in HASL's research program.

• Stanford Univ. has established a nuclear technology laboratory within its Harris J. Ryan High Voltage Laboratory. Coincidentally, it has begun construction of a $124,000 biophysics laboratory within its W. W. Hansen Laboratories of Physics. Initial biophysical research projects, upon completion of the lab this summer, will include X-ray microscopy, radiation physics, experimental high-energy electron therapy of cancer, paramagnetic resonance studies of free radicals, cellular radiobiology and radiation chemistry.

Eventually, the nuclear technology lab will also house Stanford's subcritical assembly and its projected 10-kw training and research reactor.

• 21 students from 18 foreign countries have completed the preliminary course on nuclear technology at North Carolina State College and have moved on to the International School of Nuclear Science and Engineering at Argonne for more advanced study.

• A broad range of study aid opportunities—teaching assistantships, research assistantships and fellowships—are available for the 1958–59 academic year at Carnegie Institute of Technology, Pittsburgh. Fields include nuclear science, physics, and chemical, civil, electrical and mechanical engineering. In addition to departmental laboratories, there is a Nuclear Research Center and a Metals Research Laboratory whose facilities and senior staff are available. Contact: Dean of Graduate Studies.

Courses

The Argonne National Laboratory has scheduled its second review of **nuclear fundamentals for high school teachers.** Four sessions, each spanning 2½ weeks, are tentatively slated for the periods June 9–25, June 30–July 17, July 21–Aug. 6, and Aug. 11–27. More than 400 radioactivity and high school demonstration kits, costing $125,000, have been purchased as course aids.

Nine **nuclear institutes for engineering educators** will be held at as many points across the country this summer under the sponsorship of AEC and the American Society for Engineering Education. More than 225 teachers will get special instruction in nuclear education programs for engineering students. AEC has put up some $400,000 to fund four institutes for teachers with no special nuclear background, four advanced courses and a basic course for teachers in technical institutes. All courses begin in June, end in August.

The tenth in a National Industrial Conference Board series of **atomic energy courses for management** will be held April 14–19 at Westchester Country Club, Rye, N. Y. Tuition fee is $480.

The Naval Research Laboratory, Washington, D. C., is sponsoring an experimental series of **seminars on basic science and engineering** for elementary, junior high and high school teachers. The twice-a-month series began February 15 and will run through May 19.

An intensive summer course in **automatic control** will be offered at Michigan Univ. College of Engineering, June 16–25, for engineers. Contact L. L. Rauch, East Engineering Bldg., Michigan Univ., Ann Arbor.

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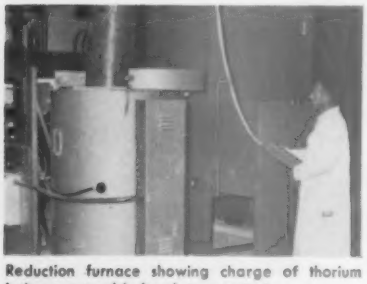
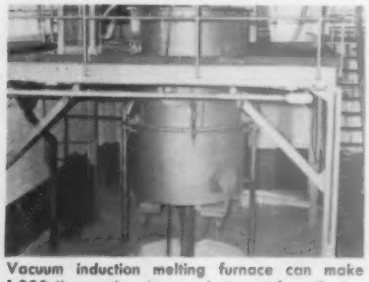
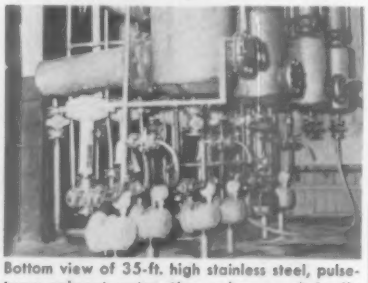


Reduction furnace showing charge of thorium being removed in bomb-type retort.

"Wet" area where uranium and thorium materials are processed in liquid media.



Vacuum induction melting furnace can make 1,200 lb. uranium ingots, designed for alloying and special castings to 3,000 lb.



Bottom view of 35-ft. high stainless steel, pulse-type solvent extraction columns originally developed by AEC.

NUCLEAR CALENDAR

March 17–21—Nuclear Congress will include four events, at International Amphitheater, Chicago: **A.** Fourth Nuclear Engineering & Science Congress (EJC), running all five days. Contact congress manager, American Institute of Chemical Engineers, 25 West 45 St., New York 18. **B.** Atomic Industrial Forum Atom Fair, all five days, contact J. V. Friel, 304 Architects Bldg, Philadelphia 4. **C.** Sixth Hot Laboratories & Equipment Conference, 19–20th; contact Frank Ring, Jr., ORNL, Oak Ridge, Tenn. **D.** Sixth Atomic Energy in Industry Conference, National Industrial Conference Board, 17–19th; contact John J. McMahon, 460 Park Ave., NYC.

March 24–27—National Convention IRE, New York (*Waldorf, Coliseum*). 275 papers in 55 sessions. Contact E. K. Gannett, IRE, 1 E. 79 St., N. Y.

March 26–28—20th meeting, American Power Conference, Chicago (*Sherman*). Contact R. A. Budenholzer, Illinois Institute of Technology, 3300 Federal St., Chicago 16.

March 27–29—American Physical Society, Chicago (*Univ. of Chicago Study of Metals Institute*). Solid state and high-polymer physics programs. Contact K. K. Darrow, Columbia U., N. Y.

March 31–April 2—Symposium on Applications of Electron and Nuclear Resonance in Chemistry, The Chemical Society, Bristol, Eng. Contact The Chemical Society, Burlington House, London, W. 1.

March 31–April 2—Conference on utilization of atomic energy, Texas A. & M. College, College Station, Tex. Will cover reactors, isotopes, waste disposal, petroleum applications, education. Contact R. E. Wainerdi, Texas A. & M., College Station.

April 7–8—Symposium on industrial utilization of radioisotopes at Loyola College, Baltimore. Sponsored jointly by Loyola, AEC, Baltimore Applied Nucleonics Society, and Baltimore Assn. of Commerce. Contact Henry T. Douglas, Baltimore Assn. of Commerce, 22 Light St., Baltimore 2 Md.

April 8–10—Brooklyn Polytechnic Institute international symposium on electronic waveguides, New York (*Engineering Societies Bldg., 33 W. 39 St.*). Includes papers on microwave properties of high- and low-density plasmas. Contact Jerome Fox, Brooklyn Polytech, Bklyn. 1, N. Y.

April 19–25—Thirteenth National Industrial Health Conference, Atlantic City. Emphasis on hazards introduced by changing technology, including radiation. Contact Mrs. Tula S. Brocard, Rm. 2029, Temporary R, 300

Independence Ave., S. W., Washington 25, D. C.

April 20–23—Canadian–U. S. chemical engineering conference, American Institute of Chemical Engineers and Chemical Institute of Canada, Montreal. Contact H. R. L. Streight, DuPont Co. of Canada, PO Box 660, Montreal, Quebec, Canada.

April 27–May 1—Annual spring meeting, Electrochemical Society, New York (*Statler*). Symposium on "The Preparation, Evaluation and Uses of High-Purity Metals." Contact M. A. Steinberg, Horizons, Inc., 2906 East 79th St., Cleveland 4, Ohio.

May 1–4—Italian Society of Radiology and Nuclear Medicine, 20th Congress, Cagliari, Italy. Contact Society, Via Comelico 2, Milan.

May 2—Fifth Annual Conference for Engineers and Architects, sponsored by Ohio State University's College of Engineering, Columbus, Ohio. Session on nuclear engineering, including power reactor trends, nuclear fuel processing, waste disposal, metallurgy and cost of nuclear fuel, and nondestructive testing of nuclear components. Contact Ohio State Univ. Bureau of Public Relations, Columbus.

May 24–31—International Water Supply Assn., 4th Congress, Brussels. Lecture on atomic energy and its relation to water supply. Contact L. Millis, International Water Supply Assn., 10 Square Ambiorix, Brussels 4.

May 27–29—Third annual reactive metals conference, American Institute of Mining, Metallurgical and Petroleum Engineers, Buffalo (*Statler*). Contact S. F. Urban, National Lead Co., Buffalo, N.Y.

June 2–5—American Nuclear Society annual meeting, Los Angeles (*Statler*). Contact W. R. Hainsworth, Fluor Corp., Los Angeles.

June 2–6—Symposium on the Peaceful Uses of Atomic Energy in Australia, Sydney. Exhibition and five-section conference—materials, power engineering, power auxiliaries (fuel cycles, chemical processing, economics), basic sciences (nuclear and thermonuclear), and associated techniques (radioisotopes, handling instrumentation, health, education, training). Contact Symposium General Secretary, AAEC Research Establishment, Sutherland, New South Wales, Australia.

June 2–7—International Conference on Solid State Physics in Electronics and Telecommunications, Brussels. Scheduled in conjunction with Brussels Fair. Papers on radiation-sensitive materials, phosphors, electroluminescent materials, infrared detectors, image amplifiers, light amplifiers, etc. Contact General Secretary, Société Belge de Physique, Loverval, Belgium.

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(Continued on pages 144 & 145)

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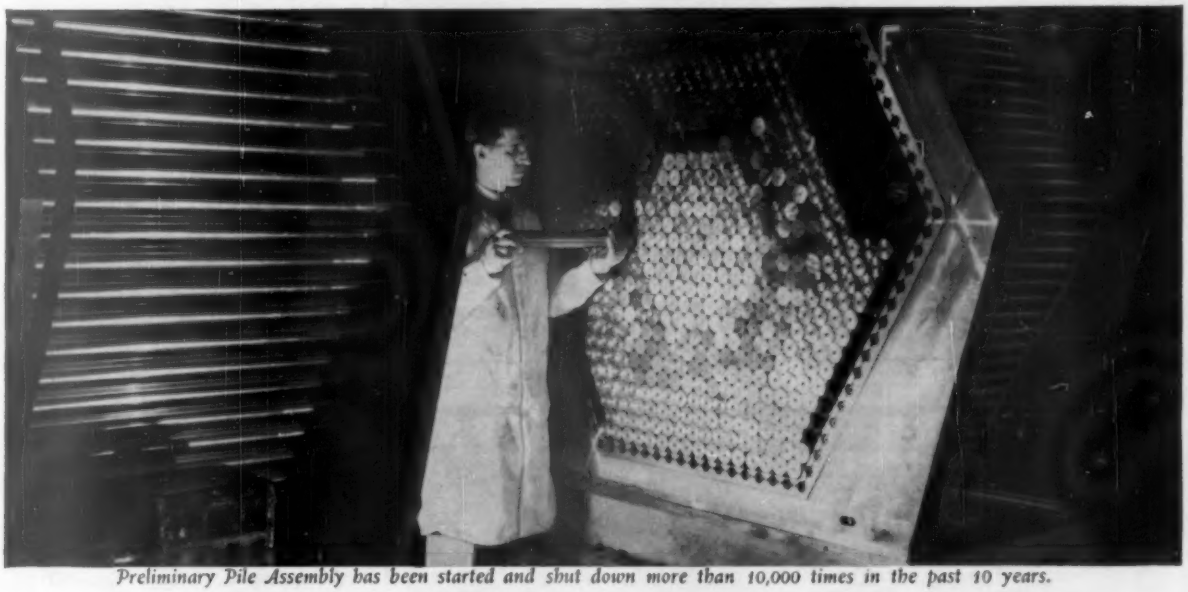

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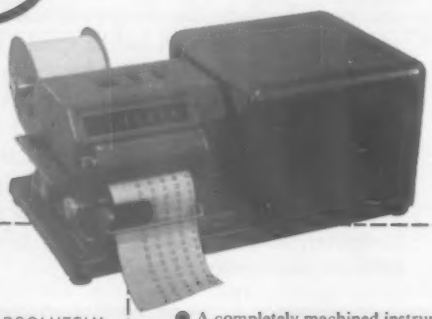

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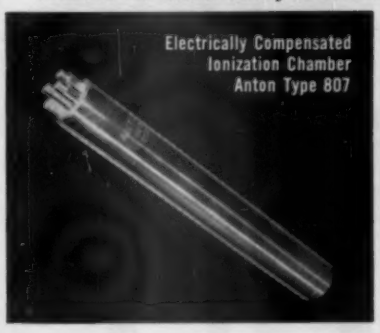

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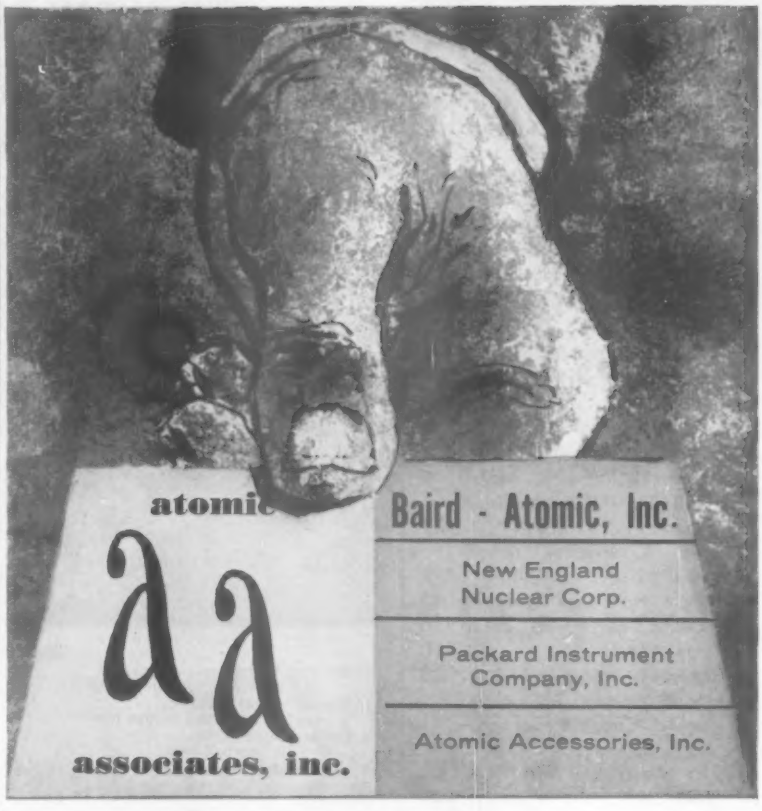

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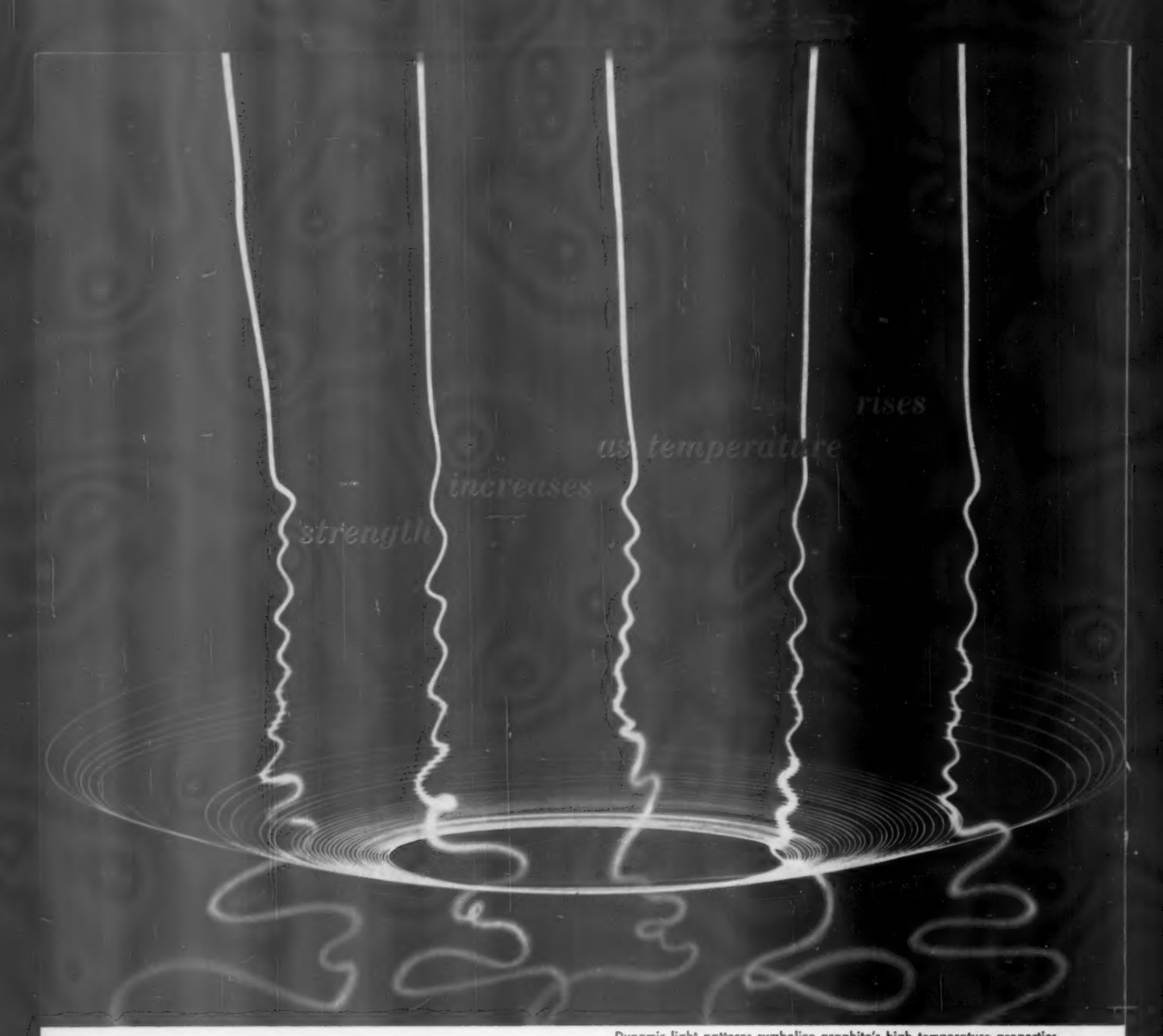

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